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BELL AEROSYSTEMS -A textron COMPANY

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BELL AEROSYSTEMS COMPANY

DIVISION OF BELL AEROSPACE CORPORATION

DESIGNERS' GUIDE

FOR

POSITIVE EXPULSION

TANK BELLOWS

Reprinted from Report No. 8230-933010

February 1967

NOTICE

Since the initial publication of this tentative Design Guide in March 1965, some revisions have been suggested. For example, the graphs in Section 3 will include properties of typical ripple shapes common to the current state of the art. These values will be presented without showing the actual ripple assumed, to protect the proprietary rights of the bellows manufacturer. The relative merits of available ripple designs vary with the specific application, though the differences are small enough to allow use of typical values for preliminary design purposes. Final evaluation of available designs may be made using Section 5.

The graphs of Section 3 can be used for design applications other than positive expulsion. By extension of Figure 3.0-2 to include higher pressures, this graph can be used together with Figures 3.0-4 and 3.0-6 to meet a variety of pressure and axial extension design requirements. The graphs of Section 3 will probably appear as carpet plots for greater ease in interpolating between values of the design variables.

Section 4, Dynamic Considerations, has been partly rewritten and updated to point out those areas which appear to have the greatest potential influence on dynamic bellows design parameters. Recognition of these further considerations has resulted from the tests and studies performed since the tentative design guide was first published. As these investigations continue, the areas most relevant to bellows design parameters will be analyzed further.

1b.

BELL AEROSYSTEMS COMPANY

DIVISION OF BELL AEROSPACE CORPORATION

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FOR

EXPULSION TANKS BELLOWS

1.0   INTRODUCTION

The characteristics of the welded metal bellows make it attractive for use as a positive expulsion device. The bellows should be seriously considered whenever reliability is a prime consideration, such as in manned flight. Other considerations recommending the bellows are requirements of low permeation rates through the gas-liquid barrier, cyclic operation, long term storage of propellants, and long term space missions resulting in long exposure to high radiation levels.

In the ensuing sections of this guide, a step by step design procedure is outlined. In its present state of development, the guide will not necessarily provide a complete and practical working design. The design charts shown were developed from parametric study of bellows extension to relatively low elastic stress levels and, consequently, will produce an overweight design. However, the extended pitch might be increased over existing designs by cyclic testing of the design selected using this guide, thus requiring fewer convolutions for the bellows. Based on the assumption that the best design in the inelastic range is the same as that in the elastic range, such a procedure may produce the lightest weight design commensurate with the current state of the art.

The basic problem of designing the positive expulsion bellows tank for minimum weight involves designing the tank and bellows in combination. The tank design is not within the scope of this contract; however, the design charts are arranged so that the designer may determine the minimum bellows weight for any given diameter of tank together with the tank length requirements. The bellows tank configuration and structural design are assumed to have been performed by the designer so that its weight contribution is available for the design evaluation process. By a repeated application of the design process to a variety of diameters, the minimum combined weight can be found which meets the envelope restrictions of the problem.

One important design condition is discussed here because its influence on weight warrants some special consideration. Since the differential pressure required to expell propellant from the bellows is small, the most critical pressure condition is produced by the tank filling pressure as the bellows extension becomes restrained by the tank end. The stresses added by the tank filling pressure must be accommodated by a reduction of the extended bellows pitch. The greater the filling pressure, the greater the number of convolutions required for a given propellant volume. A weight penalty may be said to exist, therefore, because of a lack of sophistication in the ground equipment for filling the propellant tank.

2.0   MATERIAL SELECTION

The first bellows design step is to select candidate materials. Only those materials which are compatible with the propellant to be contained should be considered. A complete bibliography on the subject of material compatibility is contained in Reference 1A.

The list of possible candidate materials can be reduced further by considering only those that remain ductile when welded and have good formability. Some materials require that welding be performed on a particular heat treated state with further post welding heat treatment to obtain the desired properties and preserve metallurgical stability. The bellows assembly process, including attachment to the tank, must be considered (to assure that the required welding and heat treatment sequence can be performed) before selection of such materials as possible candidates.

The lightest weight bellows will generally be obtained using a material which has the highest ratio of allowable strain to density. The allowable strain is that value at which a particular material can safely sustain a given number of reverse bending cycles corresponding, in this case, to the expulsion cycle requirements. If the number of expulsion cycles is large (>1000) cycles, the allowable strain may be obtained from typical S/N data to be found in Reference 2A and 3A. If the number of expulsion cycles is small (<1000), the allowable strain will involve plastic as well as elastic strain. Such low cycle fatigue problems are commonly encountered in structures under thermal stress. While the methods relating total strain to low cycle fatigue in References 5A through 7A are used for thermal stress problems, they are equally applicable to total strain from direct loading such as encountered in the expulsion bellows.

The generation of S/N data not contained in literature which is directly applicable to the vibration conditions is necessary to examine dynamic stress margins of safety. As an example, Figure 2.0-1 shows total strain range versus cycles to failure for annealed 347 stainless steel sheet undergoing uniaxial bending only. Data should be obtained which considers the bi-axial stresses present during the dynamic mechanical environment; i.e. combinations of the hoop compressive stress and the longitudinal bending stress.
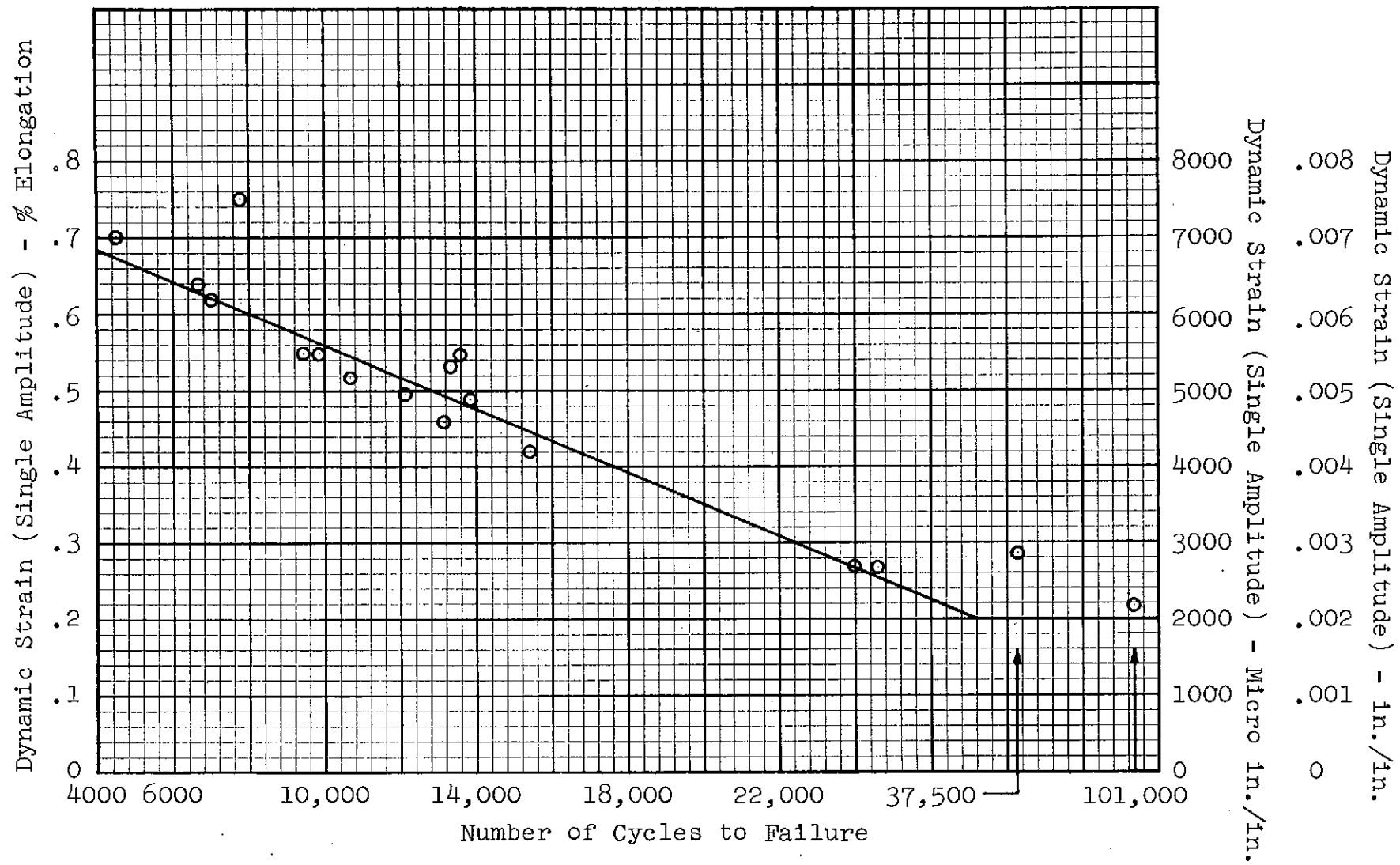
FIGURE 2.0.1   FATIGUE LIFE OF 347 STAINLESS STEEL ANNEALED
FOIL SPECIMENS DURING BENDING LOADING

The bellows must be welded to the tank. Therefore, the bellows and tank materials must be a weldable combination. The lightest weight of either tank or bellows alone may not produce the lightest combined weight. Design studies are recommended, therefore, using a few of the most promising materials in order to obtain the minimum weight bellows tank.

3.0 GEOMETRIC CONFIGURATION SELECTION

Some design charts are given in this section that are based upon an elastically deformed steel bellows with a maximum stress of 30KSI. The charts are based upon the assumption that the convolution deflection from neutral pitch is equal in either extension or compression. The charts are based upon parametric study of three basic bellows leaf contours that showed the single arc shape to produce the lightest bellows. Should the designer wish to investigate other leaf configurations, materials, or stress levels similar charts may be constructed from data gathered using Section 5.0 of this guide.

A suggested design procedure for use with this section is as follows:

1. Select one of the candidate materials from Section 2.0

2. Select a tentative bellows O.D. (Tank diameter)

3. Selecting a tentative bellows span, enter the graph of Figure 3.0-1 appropriate to the material and specification expulsion duty cycles. Record from the graph the propellant volume/convolution for several thicknesses.

4. Enter the appropriate graph of Figure 3.0-2 with the specification maximum tank filling pressure and apply the factor obtained for each thickness to the values from step 3.

5. Enter the appropriate graph of Figure 3.0-3 to obtain the convolution weight.

6. Divide the step 5 values into the values from step 4 to produce the volume of propellant loadable per pound of convolution weight. Plot these values vs. thickness to determine the optimum leaf thickness for a particular bellows span, diameter and material.

7. Divide the value from step 4 corresponding to the optimum leaf thickness from step 6 into the loadable propellant volume required by the specification. The result is the required number of convolutions for a particular bellows span, diameter and material.

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8. Multiply the value from step 7 by the step 5 value corresponding to the optimum thickness. The result is the bellows convolution weight. Add to this value a weight estimate of the bellows end closure. The design of the end closure is determined more by the tank configuration then by the bellows and is not included in this guide. This step gives the total bellows weight.

9. Enter the appropriate graph of Figure 3.0-4 obtaining for the particular diameter, span, material and thickness, a nested to extension convolution pitch change. Correct this value for tank filling pressure effect using the appropriate value from Figure 3.0-2 (Step 4). To the result, add the nested convolution pitch, which is 3 times the leaf thickness plus a clearance allowance between welds. This result is the axial length required to accommodate each convolution.

10. Multiply the result from step 9 by the value from step 7 to find the required tank cylindrical section length. Using this value, the total tank weight is determined including the tank ends and the total bellows weight from step 8.

11. Return to step 3. Using different spans in turn, repeat steps 4 thru 10. Plot the resulting weights versus span to obtain the optimum tank weight for a particular bellows tank diameter and material.

12. Return to step 2. Using several diameters in turn, repeat steps 3 through 11. Plot optimum tank weight versus bellows diameter to find the optimum bellows tank weight for a particular material.

13. Repeat steps 2 through 12 for other candidate materials to obtain the lightest overall bellows tank design. Note that in this procedure it has been assumed that the specification tank space envelope is not a determining factor. Obviously, the designer should eliminate, from this procedure, those configurations which extend beyond the space restrictions.

14. Enter Figure 3.0-5 to determine the leaf contour corresponding to the final optimum tank weight.

15. Enter the appropriate graph of Figure 6A to find the bellows spring rate/convolution which is converted to the overall spring rate by dividing by the number of convolutions.

NOTE: The figures illustrated here have the potential of several pages of graphs each, though at present, only a one page graph appears which itself is incomplete. The Figure 3.0-1, for example, changes for different duty cycle requirements and materials as the volume allowed per convolution is a function of the allowable stress. As additional parametric data becomes available, the additional graphs will be added. Until the time when the "Designers Guide for Expulsion Tank Bellows" contains an extensive collection of data, the designer will be limited to educated guesses based upon experience and supported by experimental testing.

Having arrived at an expulsion bellows tank design of minimum weight, the designer should next employ Paragraph 4.0 to evaluate the dynamics of the design.
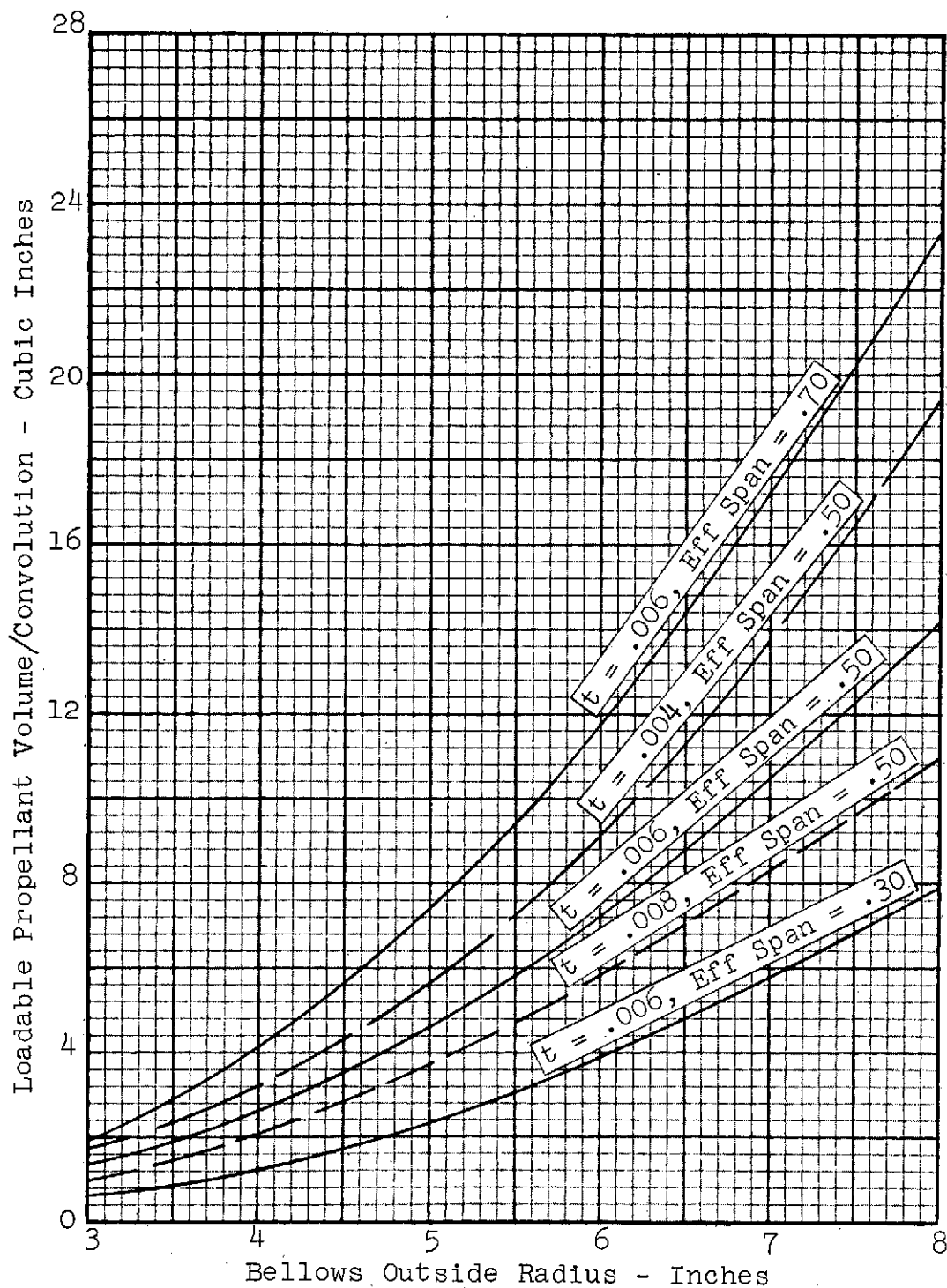
FIGURE 3.0-1 LOADABLE PROPELLANT VOLUME/CONVOLUTION
347 STAINLESS STEEL - 10,000 EXPULSION CYCLES
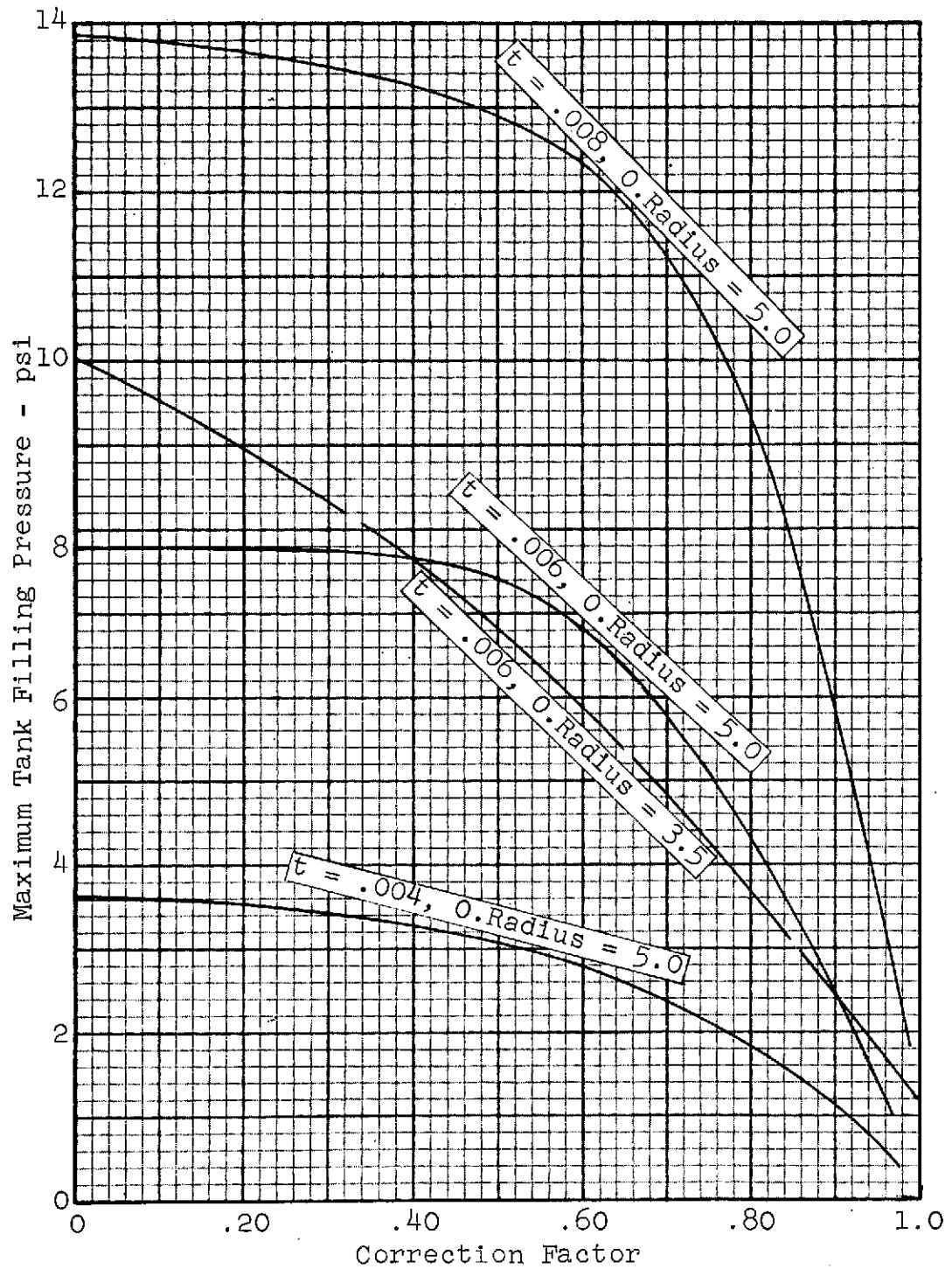
FIGURE 3.0-2 CORRECTION FACTOR FOR ALLOWABLE VOLUME AND
DEFLECTION VS. TANK FILLING PRESSURE - 347 STAINLESS STEEL
10,000 EXPULSION CYCLES
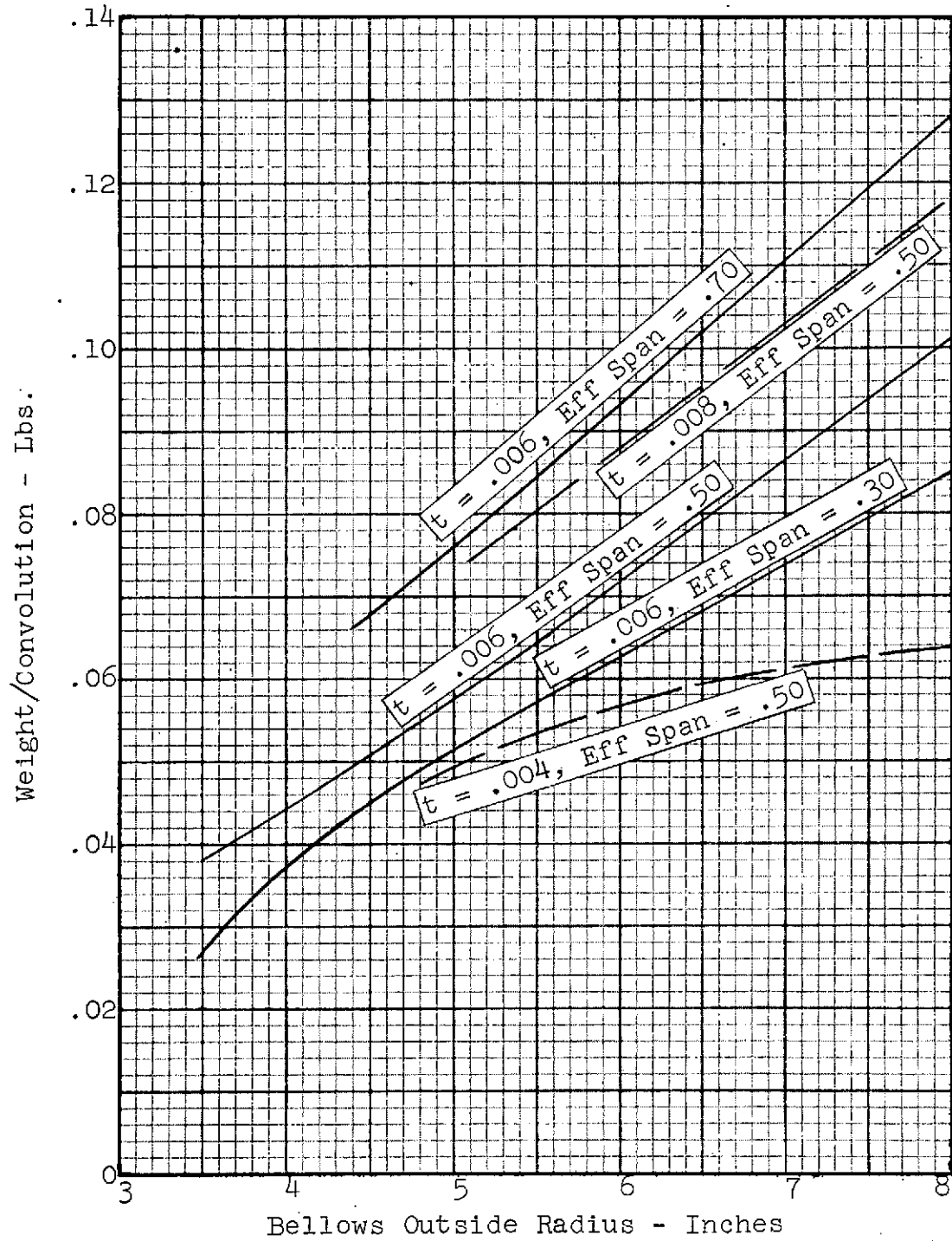
FIGURE 3.0-3   CONVOLUTION WEIGHT - 347 STAINLESS STEEL -
10,000 EXPULSION CYCLES
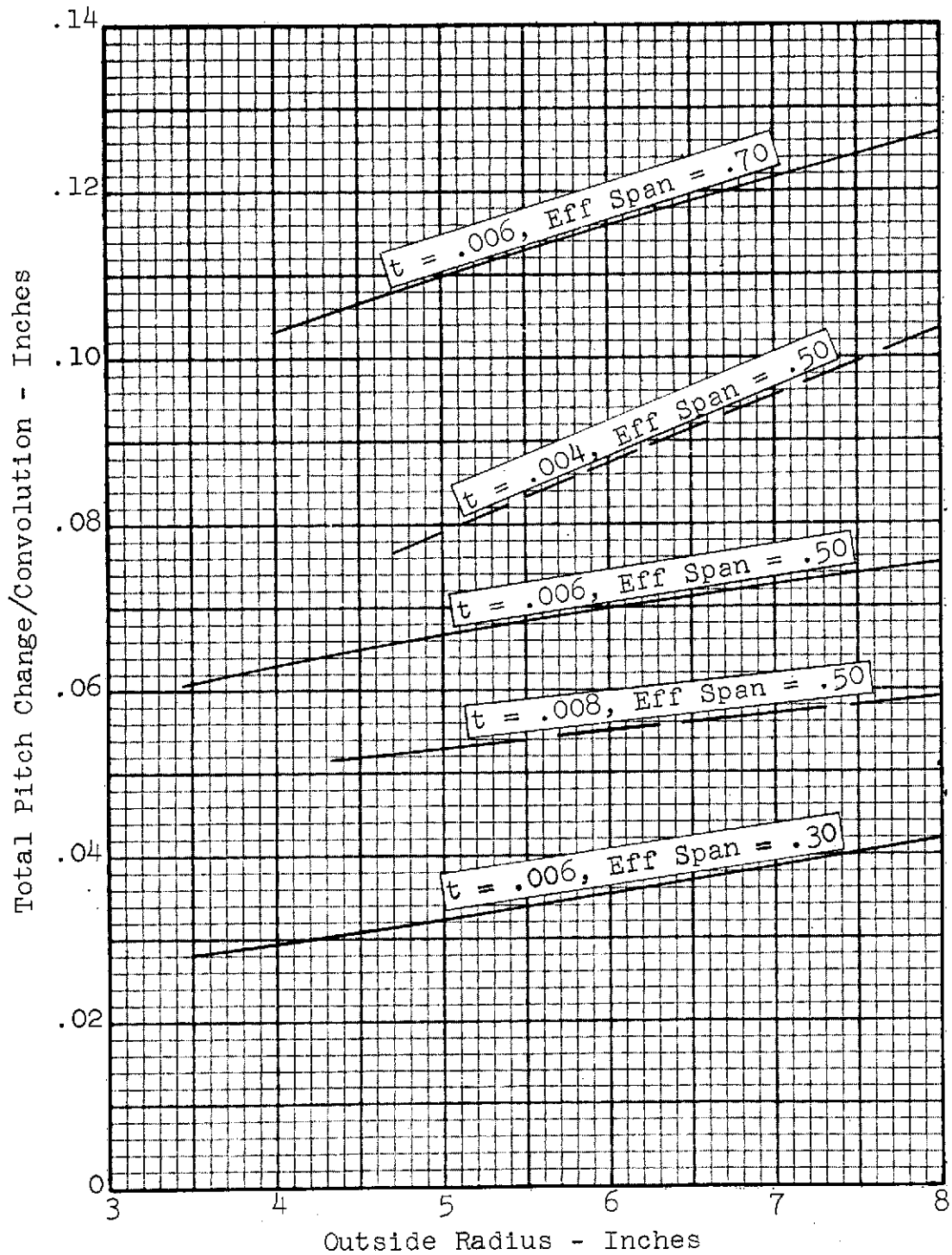
FIGURE 3.0-4 TOTAL PITCH NESTED TO EXTENDED –
347 STAINLESS STEEL - 10,000 EXPULSION CYCLES
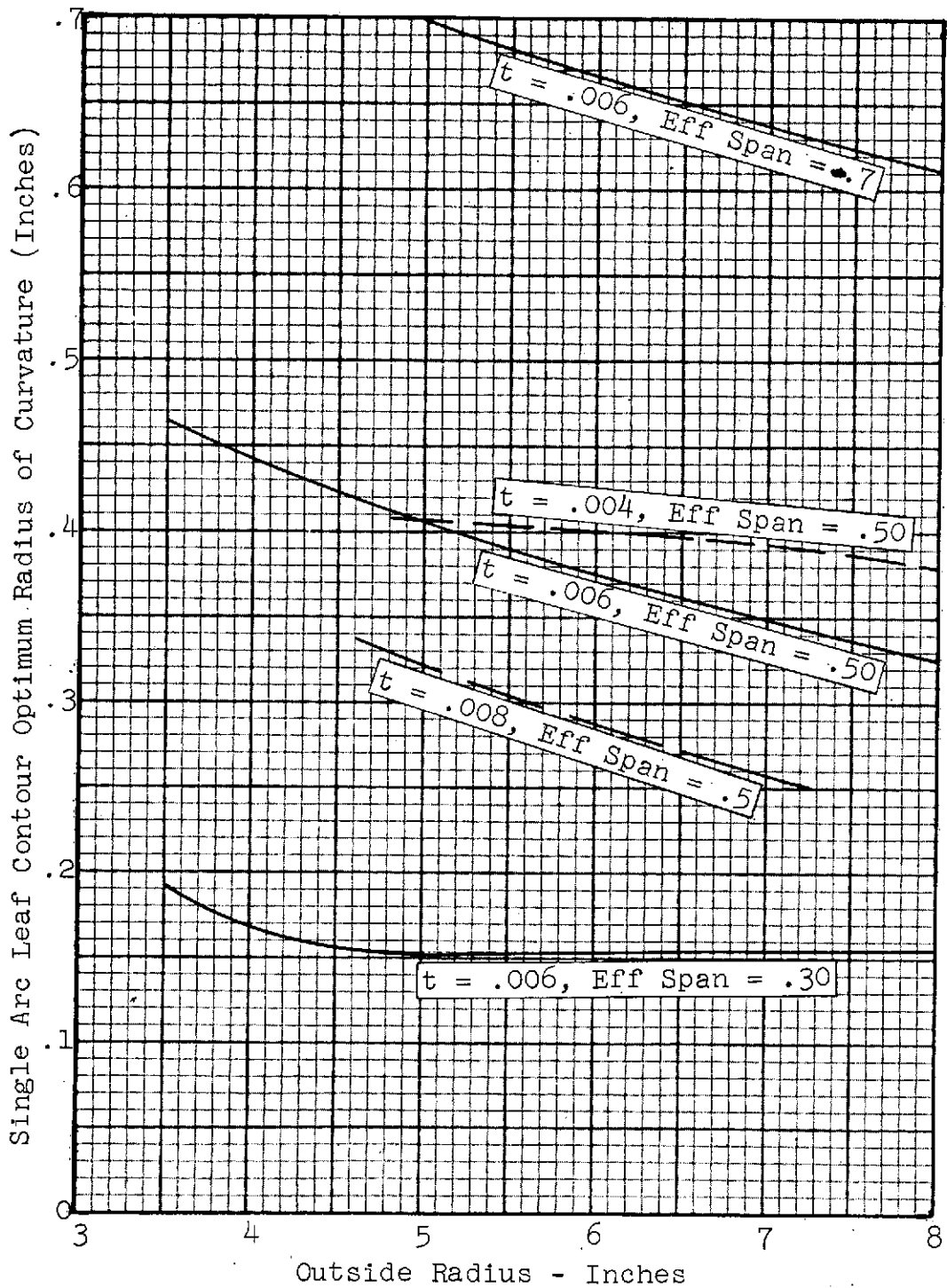
FIGURE 3.0-5   SINGLE ARC OPTIMUM CURVATURE
347 STAINLESS STEEL - 10,000 EXPULSION CYCLES
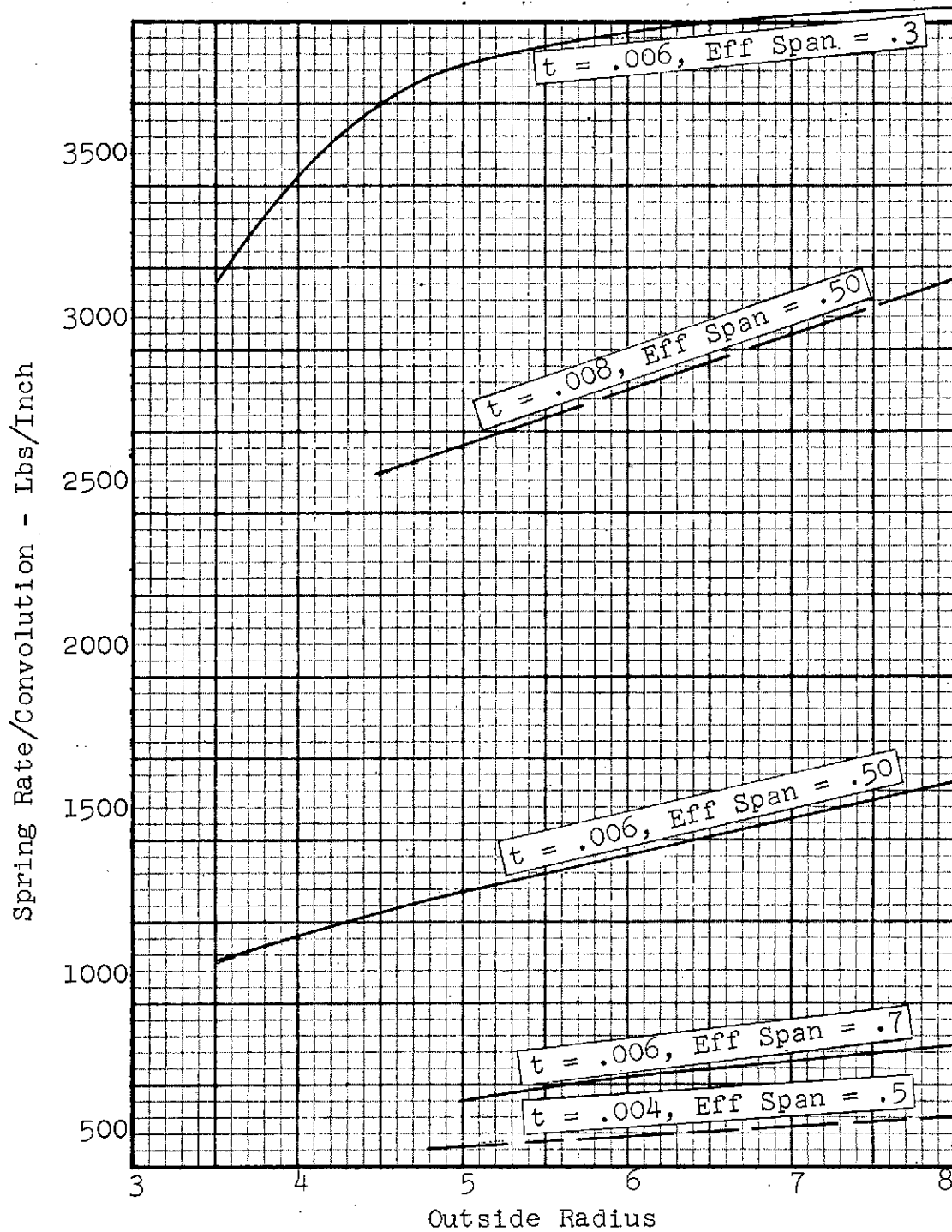
FIGURE 3.0-6 SPRING RATE/CONVOLUTION
347 STAINLESS STEEL - 10,000 EXPULSION CYCLES

4.0 DYNAMIC CONSIDERATIONS

4.1 General Discussion of Dynamic Considerations

This section will present the necessary information required by a bellows designer to properly account for bellows adequacy under the service conditions as defined by his specification.

A flight-worthy bellows must be capable of completely expelling vaporless fluid after being subjected to severely induced mechanical environments such as sinusoidal vibration, random vibration, shock, acoustic noise, constant acceleration, and pressure surges. Structural failure of bellows core or tank shell will compromise the mission. In the preliminary design stage after weight or space is optimized for the desired propellant load, dynamic considerations should be reviewed for immediate alterations in the bellows core geometry, shell clearances, and method of attachment.

The following sections present the results of studies conducted at Bell Aerosystems Company to enable the designer to recognize critical dynamic problem areas. For a bellows, these areas are discussed with sample calculations given for major response modes, namely the accordion mode, liquid mode, and the lateral mode.

These studies were conducted considering liquid propellant storage inside the bellows core and external pressurant gas. This configuration appeared to be the most attractive from an expulsion and volumetric efficiency standpoint. Tank reversal, i.e. external liquid and external gas, has considerable merit dynamically if the service environment is such that all of the mechanical excitation occurs with the bellows in the nested position.

4.1.1 Identification of Potential Failure Modes During Dynamic Testing

Discussion and examples of fatigue failures on bellows will be presented here. These will include fatigue in the heat affected zone on nesting type welded bellows and fractures through the bellows outer and inner diameter edge radii on nesting type formed bellows.

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Non-symmetric leaf buckling with and without fatigue fractures on nesting type welded and formed bellows will also be discussed.

The dynamic testing environments will include sustained acceleration, machine shock (drop), sinusoidal vibration, random vibration, and angular oscillation in both longitudinal and lateral directions of the bellows.

4.1.2 Discussion of Structural Dynamics Design Criteria

A clear useful relationship between the static ultimate load factors (ULF) or limit load factors presently used by structural designers and the loads resulting from dynamic amplification will be discussed here. For example, a specification design section may state the ULF value of 40 in a certain direction but also state the following dynamic design levels in the same direction:

a)	sustained acceleration	30g	1 minute
b)	mechanical shock	30g	6 millisecond pulses
c)	sine vibration	20g	sweep at 1 octave/min
d)	random vibration	0.07 g^2/cps	1 minute

This section should also indicate where these environments are likely to occur during the service life of a bellows; e.g., ground servicing, shipping container transportation, intra or interplant transportation, flight thrust chamber ignition, thrust termination, staging (pressure and pyrotechnic shocks).

4.2 Establishment of Pitch Where Leaf Buckling Will Occur

An experimental test will be described which will be used to verify the geometric configuration selection and insure accurate determination of the pitch   where leaf buckling will occur. These tests can be performed at the vendor or designer's facility on capsule size bellows.

4.3   Establishment of Effective Spring Rate

Refined dynamic analysis requires the establishment of a spring rate for each convolution at every extension position of the bellows being analyzed. For preliminary analysis to determine the resonant frequencies, it is sufficient to assume uniform leaf geometry and divide the spring rate per convolution by the number of convolutions and thereby obtain an overall equivalent spring rate.

When bellows extensions are limited to the linear elastic and geometric non-linear ranges as shown on Figure 4.3-1 on the increasing strain curve sections A and B, convolution spring rate can be obtained from paragraph 3.0 for the geometry shown therein. For other leaf geometries , elastic range spring rate may be obtained using the computer program from Paragraph 5.0. Spring rates, in the linear elastic range may be supplied by a manufacturer for his specific leaf design as presented in Reference 8A. When bellows extensions exceed these ranges into the physical non-linearity ranges, Paragraph 3.0 will eventually contain a method to obtain the spring rate. However, at the present time in this country, the spring rate for these positions, such as shown at lift-off in Figure 4.3-1 must be obtained by experimental means. If alternate leaf designs are being considered, it is recommended that the average spring rate per convolution be obtained experimentally on test capsules containing 10 to 20 convolutions. More accurate results will be obtained if a prototype bellows is used containing all the convolutions. In addition, one can establish the variation in spring rate for different bellows extensions (static pitches) to simulate missile propellant consumption. Two experimental methods are available.

The first method is to obtain head deflection measurements with a dial gage versus increasing amounts of internal pressures. Multiplying the ΔP times bellows effective area gives force which is divided by the deflection to give spring rate. The second method is to attach a massive weight and velocity pickup to the bellows head and slightly displace the head so that a decay amplitude at constant frequency, f, is displayed on a Brush recorder.

Substitution of the frequency into the following expression (Reference 10A) gave the longitudinal total effective spring rate K_A:

$$f = \frac{1}{2\pi} \sqrt{\frac{K_A}{M + \frac{m}{3}}} \qquad M = \frac{W}{g}; \quad m = \frac{w}{g}$$

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where: f = frequency of decay signal, cps

          W = attached weight, bellows head weight, velocity pickup weight, and attachment hardware, lb

          w = weight of bellows convolutions, lb
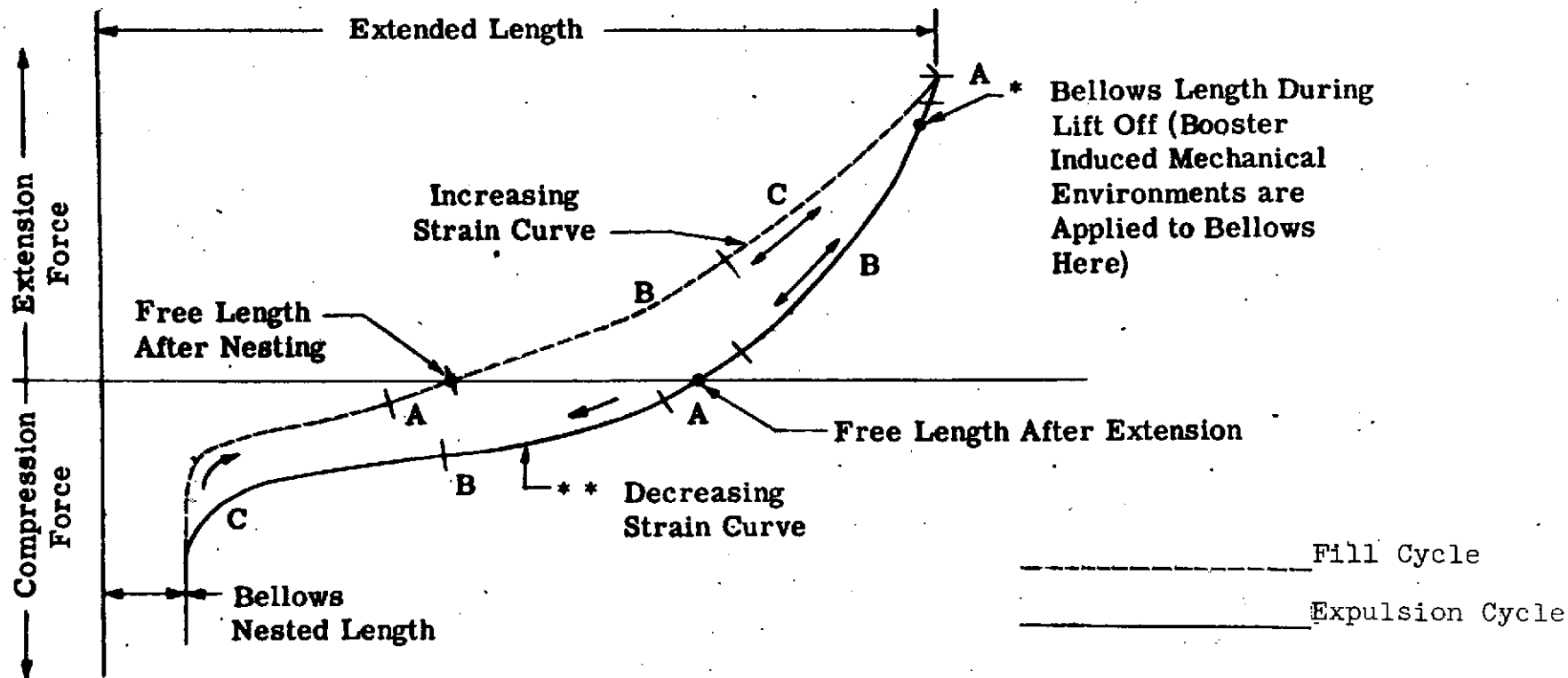
A - Linear Elastic (straight and reversible)

B - Geometric Non-linearity (curved and reversible)

C - Physical Non-linearity (curved and irreversible)

* - Represents fully loaded position. Maximum bellows capacity at extended length less ullage volume allowance for propellant temperature compensation.

** - Vibration always occurs along this curve when bellows are extended beyond linear elastic range. Because motions are relatively small during vibrations, the spring rate usually remains constant at any fixed bellows extended length.

Figure 4.3-1. Hysteresis Curve

4.4 Calculation of Bellows Response

4.4.1 Simplified formulas

SUMMARY OF BELLOWS FORMULAS

Bellows Modes	Frequency - cps
Longitudinal accordion	$f_a = \dfrac{n}{2}\sqrt{\dfrac{K_A\, g}{W_t + W_m}}$
Longitudinal liquid	$f_L = f_a\ f(ka)\ \sqrt{\dfrac{1}{\dfrac{1}{2}\left(\dfrac{d_o^2}{d_i^2} - 1\right)}}$ where $f(ka) = \sqrt{\dfrac{4}{ka\left[\dfrac{I_o(ka)}{I_i(ka)}\right]}}$
Lateral (Head Fixed)	$f_\ell = \dfrac{A_N}{2\pi}\sqrt{\dfrac{K_A\, r^2\, g}{2L^2\,(W_t + W_m + W_i)}}$
Lateral (Head Rocking)	

a   =   inside radius of liquid column, assumed as $\dfrac{d_i}{2}$

A_N =   numerical constant 22.0, 121, 298.2 ...

d_i =   inside diameter of bellows, in.

d_o =   outside diameter of bellows, in.

$I_o(\ )$ =   modified Bessel function of the first kind zero order

$I_i(\ )$ =   modified Bessel function of the first kind first order

g   =   386 in/sec^2

f(ka)=   function of bellows length and inside diameter

Approximate f(ka) values are plotted in Figures 4.4.1-1 and 4.4.1-2. Exact values are compiled using a Bessel function table.

k   = $\dfrac{n\pi}{L}$

K_A =   longitudinal total effective spring rate of all convolutions, lb/in.

L   =   length of bellows, in.

n   =   mode number and numerical constant of 1, 3, 5 ...

r   =   effective radius of bellows, assumed as $d_o/2$

W_i =   weight of liquid inside of bellows, lb. Calculate from $W_i = \dfrac{\pi}{4} \, do^2 \, L\rho$

Wm   =   weight of convolutions, lb

W_t =   weight of liquid trapped in convolutions, lb. Calculated from $W_t = 1/2 \, CP\pi \, ND_m \, \rho$

C   =   bellows span, in.

P   =   bellows pitch, in.

N   =   number of convolutions

Dm   =   bellows mean diameter, in.

ρ =   specific density of fluid entrained in bellows, lb/in.^{3}

The formulas shown in the Summary of Bellows Formulas tabulation should only be used when the internal liquid and external gas are approximately at the same pressure, i.e., a very low ΔP. Variations in this ΔP and external gas density will affect the frequency of each bellows mode as shown in Table 4.4.1.1.
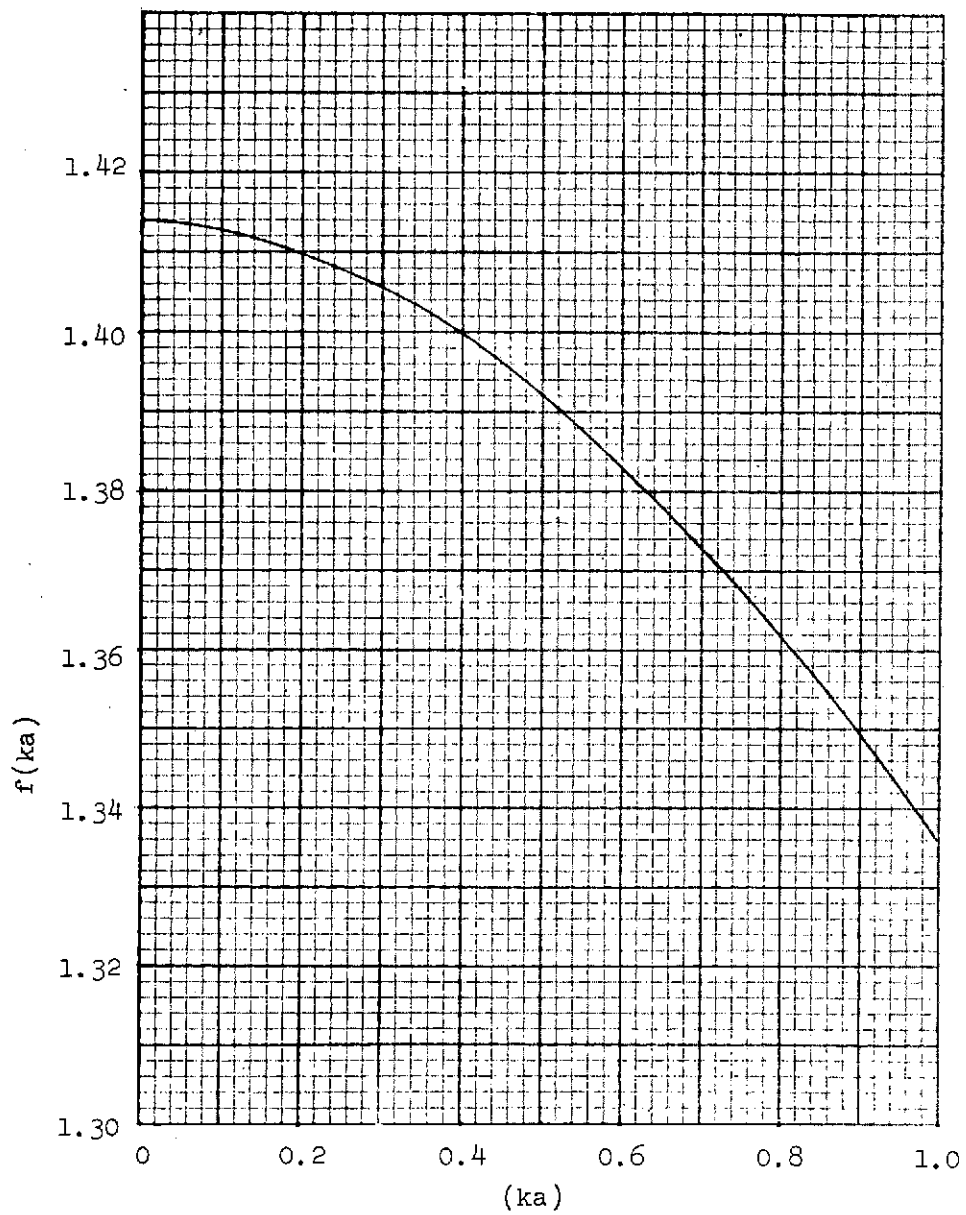
Figure 4.4.1-1.   Nondimensional Plots of Liquid Mode
Frequencies Functions, f(ka) vs (ka)
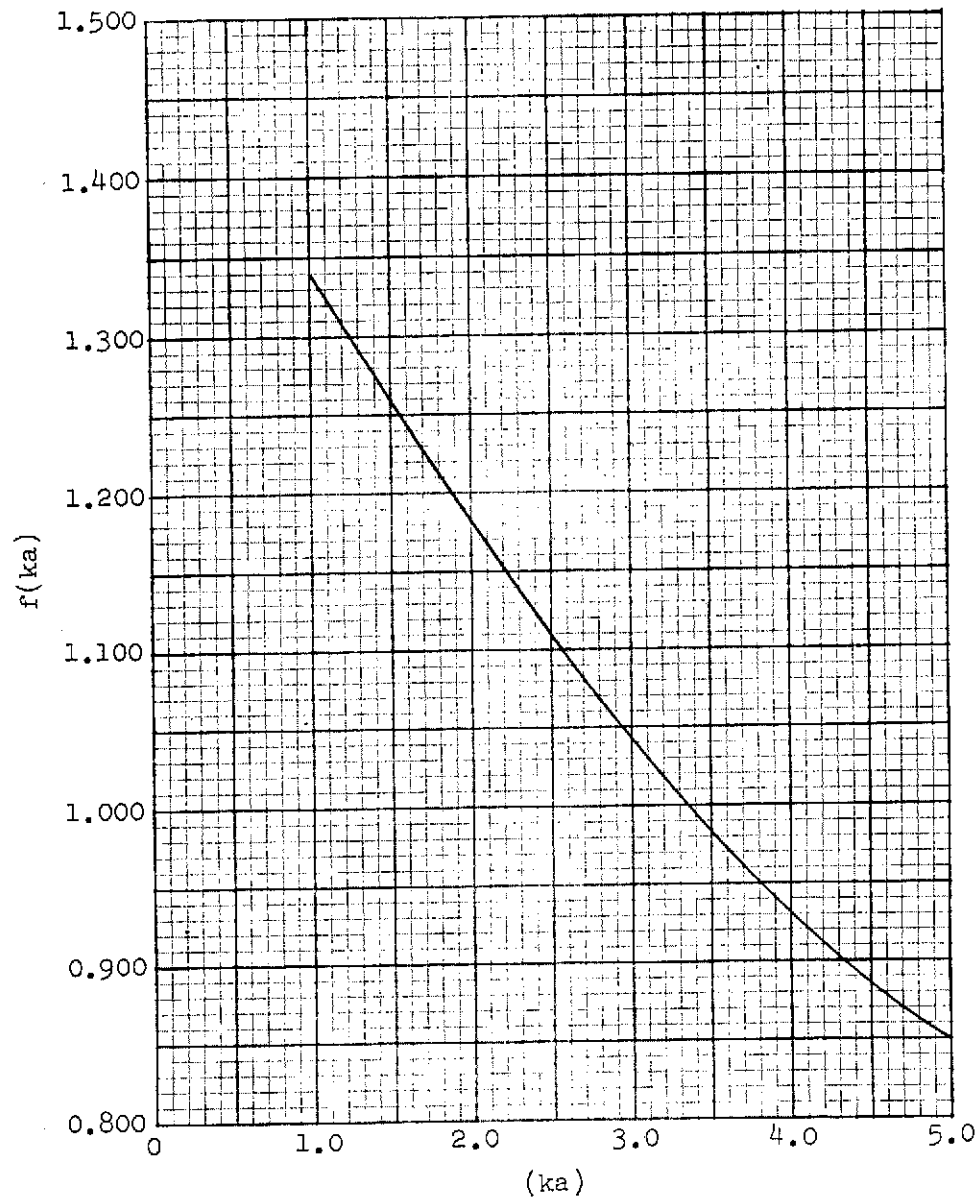
Figure 4.4.1-2.   Nondimensional Plots of Liquid Mode
Frequencies Functions, f(ka) vs (ka)

TABLE 4.4.1.1 EFFECTS OF PRESSURE VARIATIONS
AND GAS DENSITY ON THE RESONANT
FREQUENCIES OF SIGNIFICANT BELLOWS MODES

Mode	Negative ΔP External gas pressure higher than internal liquid pressure	Positive ΔP External gas pressure lower than internal liquid pressure	Same ΔP Increase or decrease in both external gas and internal liquid pressure	Same ΔP Increase in external gas density
Longitudinal Accordion	None	None	None	None
Longitudinal Liquid	Unknown	Unknown	None	Changes
Lateral (head restrained)	Increases	Decreases	None	None
Lateral (head working)	Unknown	Unknown	None	Decreases

4.4.1.1 Sample Calculation

Assume it is required to estimate the following bellows longitudinal accordion, liquid and lateral mode frequencies with small (less than 1 psi ΔP) pressure drops across the bellows.

Bellows configuration:

d_o, outside diameter, $= 4.3$in.   bellows vibration length $= 10.7$ in.

d_i, inside diameter $= 3,644$in.   number of convolutions $= 100$

$\ddots$ span $= .328$ in

W_M, bellows weight $= 1.0$ lb $\therefore$ p, bellows pitch $= .107$in

K_A, overall spring rate $= 10.8$ lb/in.

Test liquid in bellows $=$ water

4.4.1.1.1 Accordion Mode Frequencies

$$f_{a_1} = \frac{\eta}{2} \sqrt{\frac{Ka}{Wt + Wm}\ g} = \frac{1}{2}\ \frac{(10.8)(386)}{.82 + 1.0} = 23.9 \text{cps}$$

where $W_t = \frac{1}{2}\ Cp \pi N\ D_m \rho = \frac{1}{2}\ (.33)\ (.107)(\pi)(3.97)(.0362)$
$= .82$lb.

higher harmonics for $\eta = 3, 5, 7 \ldots = 71.7$cps, 119.5cps, 167.0cps ....

4.4.1.1.2 Liquid Mode Frequency

$$a = \frac{di}{2} = \frac{3.644}{2} = 1.822 \text{in} \qquad k = \frac{\eta \pi}{L} = \frac{(1)(\pi)}{10.7} = .293$$

$$ka = (1.822)(.293) = .534 \qquad f(ka)\ \text{fig } 4.4.1.1 = 1.389$$

$$f_L = f_a \cdot f(ka) \sqrt{\frac{1}{\frac{1}{2}\ (\ \frac{do^2}{di^2} - 1)}}$$

$$= (23.9)\ (1.389)\ \frac{1}{\sqrt{\frac{1}{2}\left[\frac{4.3^2}{3.644^2} - 1\right]}} = 76.3 \text{cps}$$

higher harmonics for $\eta = 3, 5, 7 \ldots$ $= 229$cps$, 382$cps$, 535$cps..

4.4.1.1.3 Calculation of Liquid Mode Frequency at Various
External Gas Densities and Pressures

At the present time, the following equation
contains terms which include both liquid and gas densities
and pressures.

$$\frac{d^2Q}{dr^2} + \frac{1}{r}\frac{dQ}{dr} - k^2 \left[1-\beta^2\right] Q = 0$$

This equation was evaluated for various boundary
conditions and should yeeld a formula which will calculate
liquid mode frequencies at various external gas densities
and pressures. The bellows-tank condition investigated is
shown below in Figure 4.4.1-3.
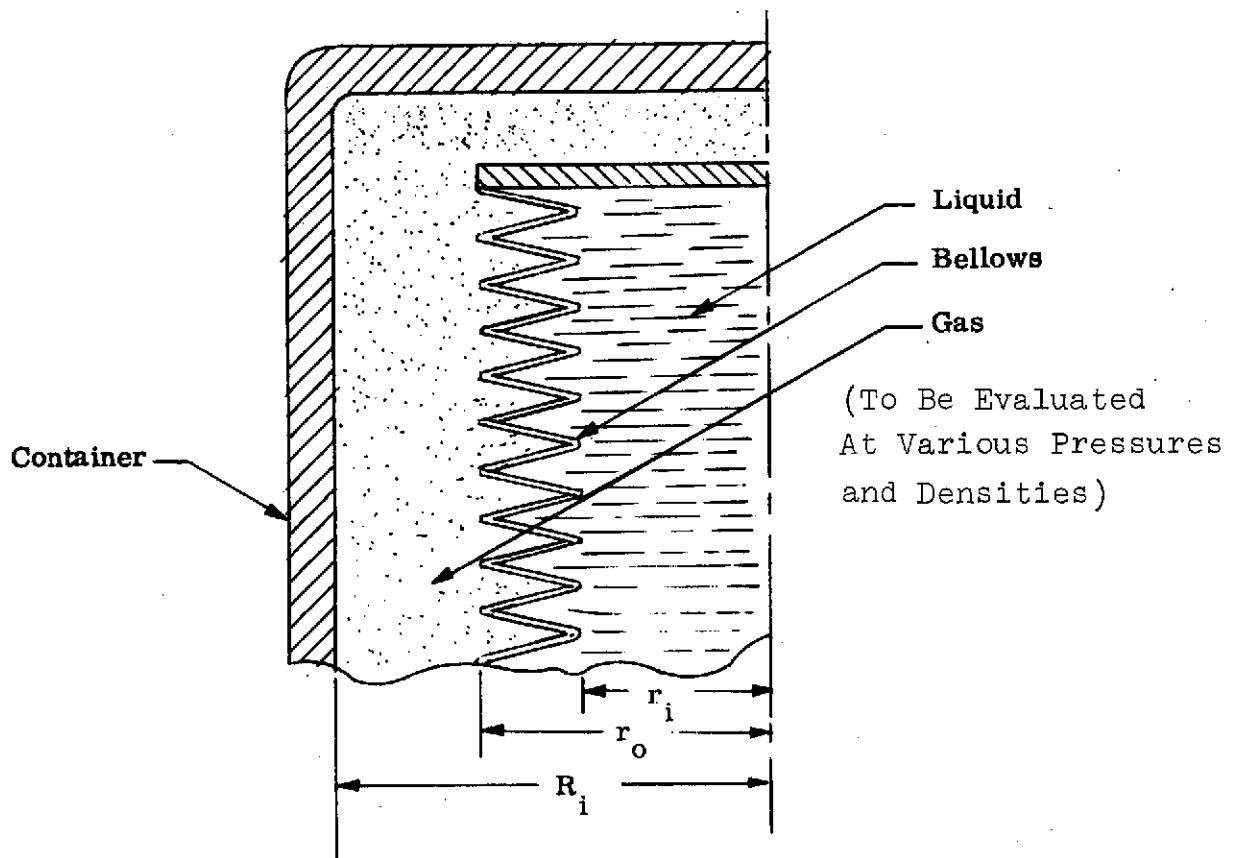
Figure 4.4.1-3 Configuration of Tank Assembly to Determine

the Effect of External Pressure on Liquid Mode Frequency

4.4.1.1.4 Lateral Mode Frequencies With Small ΔP (less than 1psi)

$$f_1 = \frac{A_N}{2\pi} \sqrt{\frac{Kar^2 g}{2L^2(W_t + W_m + Wi)}}$$

$$Wi = \frac{\pi}{4} di^2 L \rho$$

$$= \frac{\pi}{4} 3.644^2(10.7).0362$$

$$= 4.021b.$$

$$= \frac{22.0}{2\pi} \sqrt{\frac{(10.8)(2.15)^2\ 386}{(2)(10.7)^2(.82 + 1.0 + 4.02)}} = 13.3cps$$

higher harmonics for $A_N = 121,298.2... = 73cps, 180cps...$

4.4.2 Refined Analysis of Bellows Modes

4.4.2.1 Accordion Mode Analysis by Digital Computer Method

Nearly exact longitudinal or axial vibration modes, herein referred to as accordion modes, can be established for nearly any bellows configuration by use of the following matrix iteration technique which neglects damping and bellows head elastic terms. These head elastic forces may cause slight coupling with the motion of the last few convolutions attached to the head but test results showed little influence on over-all accordion mode motion. This procedure is quite useful when different bellows leaf thicknesses are used, when masses are attached at the weld beads, or when the end boundary restraints are altered.

The design guide will show how the stiffness and mass matricies are constructed for the practical bellows case.

4.4.3   Multi-Ply Bellows Response

Sales literature indicates that one major advantage of multi-ply bellows leaf construction is to provide greater resistance to static and dynamic internal or external pressure forces without a substantial increase in bellows axial stiffness that would normally result from a thicker leaf. To be effective, the adjacent multi-ply leaves should be in contact with each other. One bellows manufacturer using the TIG welding process, provides vents in the outer ply to release any trapped gases prior to a heat treatment process.

Sinusoidal vibration tests were conducted at a constant g-level to compare the dynamic response of single-ply and double-ply bellows construction. In Figure 4.4.3-1 notice that the weld bead joins two leaf metal thicknesses in a single-ply bellows and four thicknesses in a double-ply bellows.
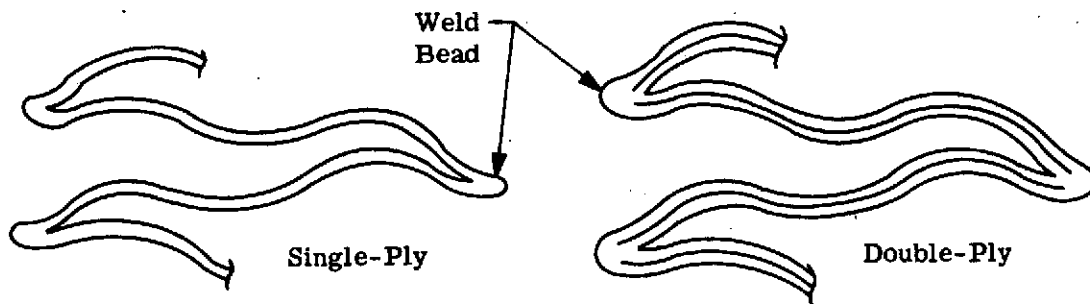
Figure 4.4.3-1

Comparison of Single-Ply and Double-Ply Bellows Construction

The spring rate of one double-ply bellows tested was 225% of the single-ply bellows; two springs directly in parallel would yield a spring rate of 200%.

The amplification factor output/input for the double-ply bellows was greater in the accordion, liquid and lateral fundamental modes. This was not expected since some fric-

tional damping should have existed between the plies. Since bellows failure is proportional to convolution pitch change and internal pressure fluctuations, this points out a slight disadvantage of going to a multi-ply construction with the same leaf thicknesses.

No unexpected phenomenon other than damping decrease was seen on the double-ply bellows. Agreement of all three major bellows resonant modes was obtained using accordion liquid and lateral formulas developed in 4.4.1.1.

4.5   Vibration Attenuation Devices

4.5.1 Accordion Mode

4.5.1.1   Protruding Baffles

One method recommended to attenuate bellows' motion is to have ring baffles welded into the bellows core at anti-nodes of accordion mode response. Figure 4.5.1.1-1 shows an installation of test ring baffles inserted so that these protruded 0.4 inch into the liquid beyond the inside weld. The optomization of protrusion depth and number of baffles for higher mode attenuation becomes a development item for each application.

One practical construction is shown below, here a third leaf is welded in at the outside diameter and protrudes into the liquid column.

Baffle

Bellows
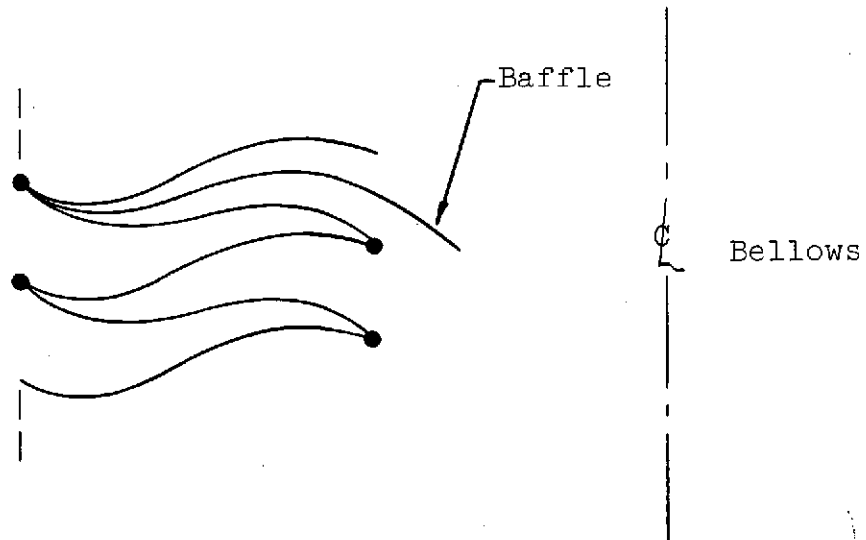
4.5.2 Liquid Mode

4.5.2.1 Pressurization Gas Control

Figure 4.5.2.1-1 shows a definite trend toward liquid mode attenuation which increased gas density; this method of attenuation is recommended. A cursory investigation was made of available industrial gases. Those that had densities greater than 2 and which could be applicable are listed in Table 4.5.2.1-1. A comparison of the significant properties of these gases is presented in Table 4.5.2.1-2. While no actual testing of performance has yet been conducted, these gases appear to have good potential for this application.

4.5.2.2 Gas Entrainment Devices

Gas entrainment devices can be inserted inside a bellows or in the propellant line to attenuate liquid pressure oscillations in the liquid mode of vibration.

4.5.2.3 Energy Dissipation

Figure 4.5.2.3-1 shows the shear viscoelastic damping method presently being investigated by Bell Aerosystems Company.

Data Taken on 6 Inch Diameter, 65 Convolution
Bellows at Approximately 34 cps
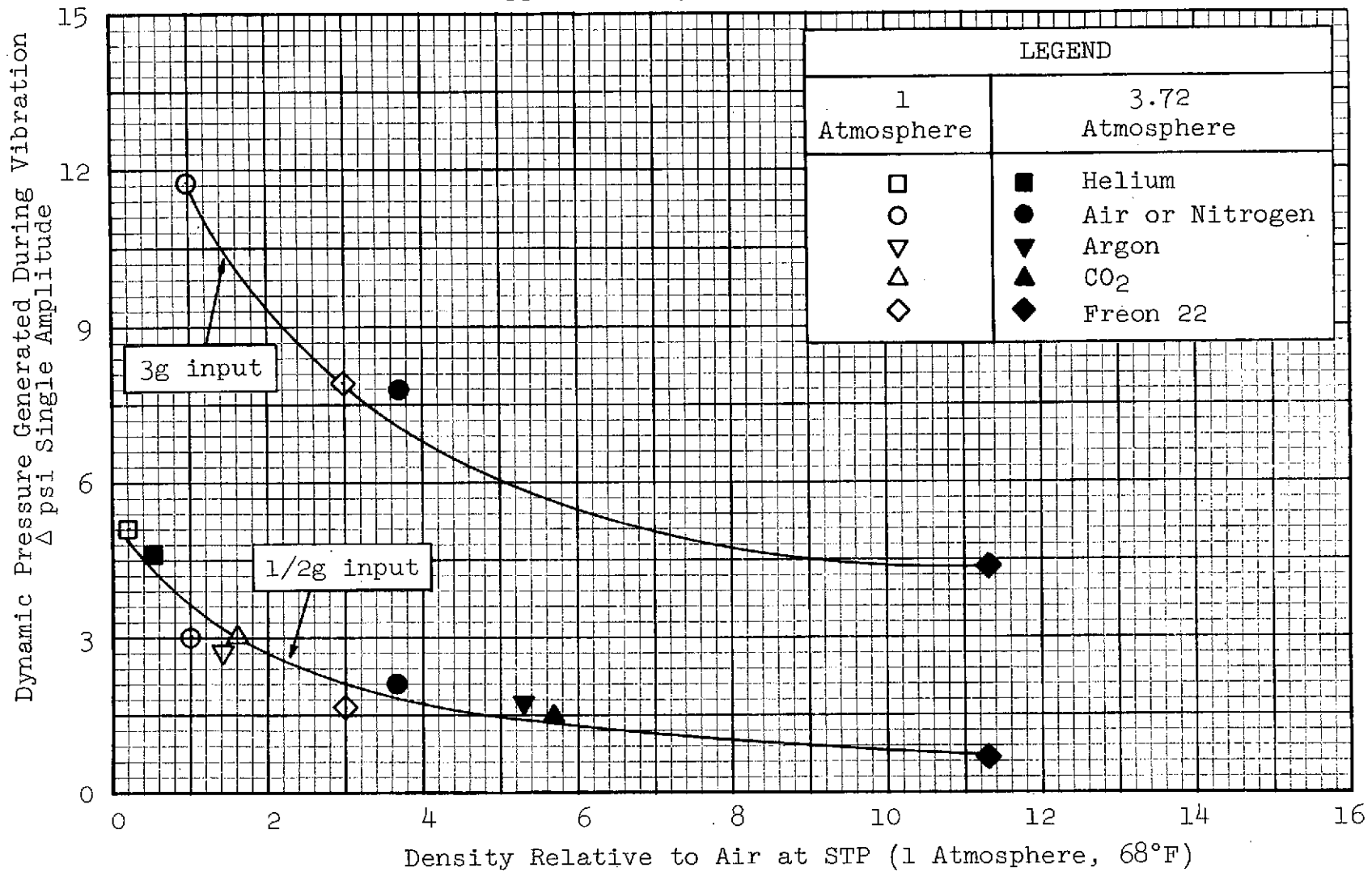
FIGURE 4.5.2.1-1 SUPPRESSION OF LIQUID MODE WITH VARIOUS EXTERNAL GASES

TABLE 4.5.2.1-1 Candidate Gases to Suppress Bellows Liquid Mode

Gas	Density Relative to Air - S.T.P. (Specific Gravity)
Freon C 318	7.08
Perfluoropropane	6.48
Freon 114	5.69
Freon 13B1	5.10
Perfluoro-2-Butene	4.85
Xenon	4.52
Freon 12	4.20
Chlorotrifluoroethylene	3.97
Genetron 21	3.82
Freon 13	3.82
Freon 22	2.97
Dimethylpropane	2.49
Genetron 152A	2.42
Ethyl Chloride	2.20
Genetron 1132A	2.18
Argon	1.38
Air	1.00
Nitrogen	.96
Helium	.14

Density Relative to Air - S.T.P.

(Specific Gravity)

Source: Matheson Gas Data Book

BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION

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TABLE 4.5.2.1-2. COMPARISON OF SUITABLE INDUSTRIAL GASES

Gas	Cost/Lb.	Boiling Point at 1 atm	Materials of Construction	Toxicity	Uses	Critical Pressure Psia	Critical Temperature °F	Vapor Pressure Psig
Argon	$ 1.09	-302°F	All Metals	Non	Inert Gas	705	-188°	
Chlorotrifluoroethylene	2.20	-18.2°	All Metals	Slight	Polymerization Additive	589	222°	62
Dimethylpropane	2.50	49.1°	All Metals	Slight	Raw Material in Isobutylene	464	321°	7
Ethyl Chloride	.45	54.3°	All Metals	Slight	Solvent (Chloroethane)	764	368°	5.3
Freon 12	.60	-21°	Stainless Steel	Non	Refrigerant	596	233°	70
Freon 13	5.40	-114.5°	Stainless Steel	Non	Low Temperature Refrigerant	561	83.8°	458.7
Freon 13B1	5.00	-72°	All Metals	Non	Fire Extinguisher Agent	574	152°	190
Freon 22	1.04	-41.4°	Stainless Steel	Non	Low Temperature Refrigerant	716	204.8°	122
Freon 114	1.20	38.4°	All Metals	Slight	Cooling Systems	474	294°	12.9
Freon C318	4.75	21.1°	Stainless Steel	Non	Dielectric Gas	393	239°	15
Genetron 21	1.70	48°	Stainless Steel	Non	Solvent	749	353°	8.4
Genetron 152A	1.10	-12.4°	Stainless Steel	Slight	Low Temperature Solvent	652	236°	63
Genetron 1132A	3.20	-117°	All Metals	Non	Preparation of Polymers	643	86.2°	518
Helium	8.96	-452°	All Metals	Non	Inert Gas	33.2	-450°	
Nitrogen	.33	-320°	All Metals	Non	Inert Gas	492	-232°	
Perfluoro-2-Butene	12.80	34°	All Metals	Unknown	Nonflammable Agent			15
Perfluoropropane	12.00	-34°	All Metals	Non	High Voltage Insulation	388	161°	25
Xenon	1973.00	-162°	All Metals	Non	Inert Gas	852	61.9°	

Head

Outer Leaf

Inner Leaf

Damping Material
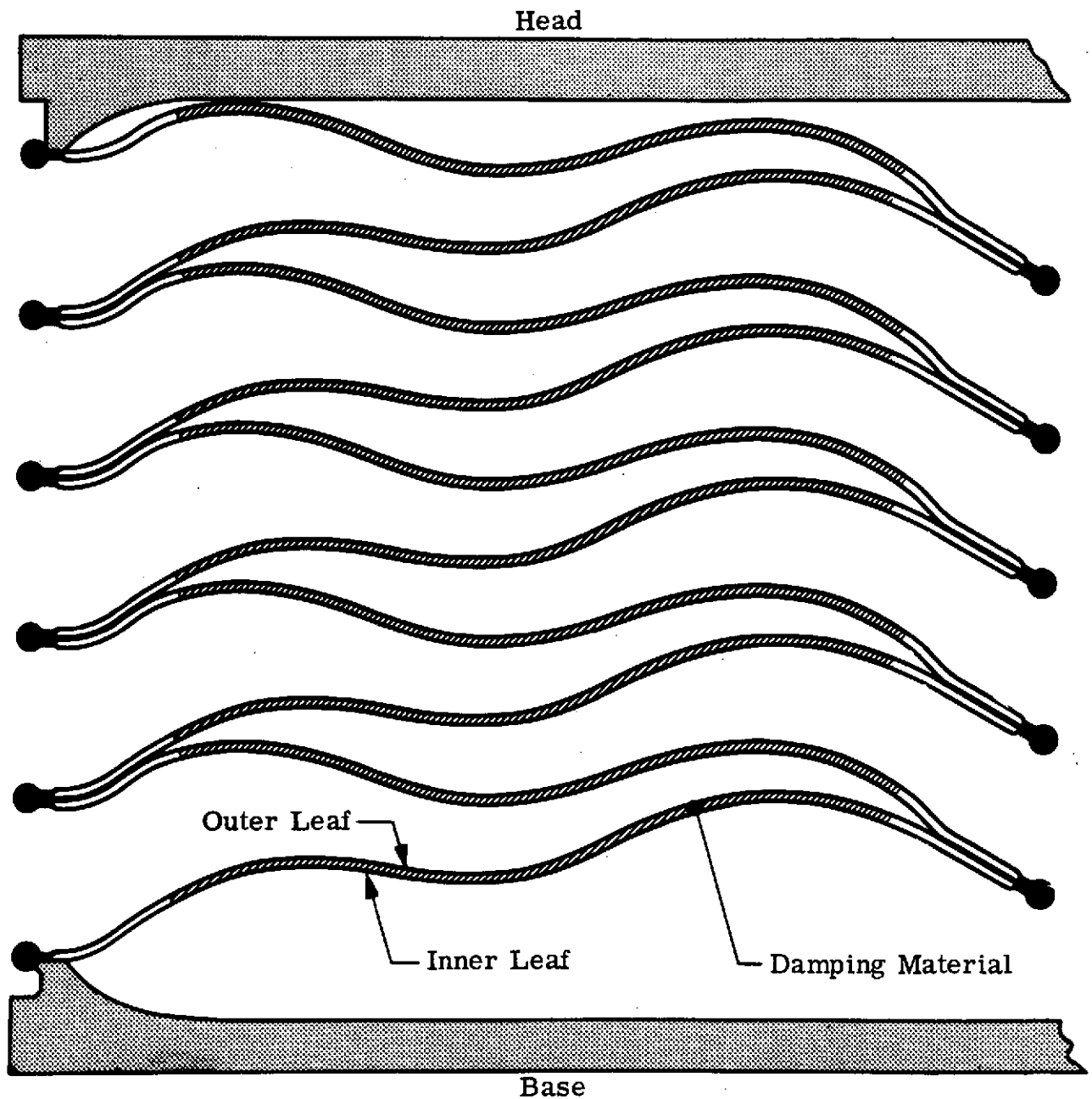
Base

FIGURE 4.5.2.3-1   CROSS SECTION REPRESENTATION
OF FULLY DAMPED BELLOWS

4.5.3   Method of Attachment
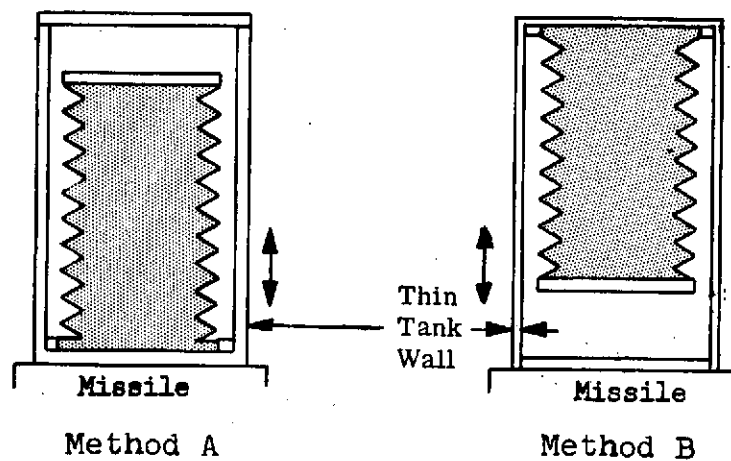
Figure 4.5.2.4-1
Comparison of Bellows Tank Configurations

        Method (a) is preferred because the bellows base
directly receives only the input vibration; in method (b),
considerable shell amplification increases the amount of
vibration getting to the bellows.

4.6 Other Dynamic Consideration

(Information to be supplied at a later date.)

4.7 Cumulative Fatigue Considerations

(Information to be supplied at a later date.)

5.0 STRESS ANALYSIS

The stress analyses of a welded bellows having any leaf contour of interest are best performed using a high speed digital computer. The applicable computer programs are being made available through the IBM Share program. Two programs have been developed. One is applicable to stresses in the elastic range and includes a subroutine to detect local leaf instabilities in either symmetric or asymmetric modes. The second program accounts for both geometric distortion and material inelasticity, including the hysteresis effects of load reversal. The programs may be employed to obtain detail stress and/or leaf distortions of either the design obtained from Section 3 or of special designs not included in that section.

The programs provide a numerical solution of the differential equations of E. Reissner, Reference 4A, for large deformations of axisymmetrically loaded shells of revolution. The method involves a tridiagonal inversion of a large matrix assembled using three point finite difference approximations at each solution point. Because of the convenient choice of coordinates used by Reissner, there is no difficulty with infinite tangents normally encountered with either flat plates or cylindrical shells. Any shell of revolution geometry, including the special flat plate case, may be solved without source program changes.

The bellows mathematical model is made up of six leaves joined at their boundaries by a weld bead ring. The weld bead cross section is a half ellipse with its half axis in the plane normal to the bellows longitudinal axis. Stress concentration effects have been neglected.

The geometric configuration is simulated by input selection of basic toroidal and conical geometric elements. The programs assemble the element selections into a continuous shell without discontinuity in any leaf. All six leaves may be different if desired. The shell thickness, however, must be constant within each leaf. Though variable thicknesses are possible, such a capability has yet to be incorporated. A variety of end boundary conditions from fully fixed to free restraint are provided. The weld beads may be omitted so that formed bellows or other types of continuous shells may be analyzed. The bellows may be extended or compressed by either a circumferentially uniform end force or by a pressure differential applied separately. Under special conditions of axial restraint, pressure and end reaction, forces are applied simultaneously.

Comments appear in the program listing for each input quantity to serve as a reminder to the user. To clarify the meaning and sign conventions, each item of input is discussed in detail below:

NTRIAL   –   any number of bellows designs may be analized without resorting to individual problem introductions to the computer. NTRIAL is the number of designs input for a computer run. Minimum cost is frequently achieved by running more than one case as the single case computation time may be much less than a fixed minimum computer time charge.

M   —   Each leaf is divided into a given number of equal spaces (finite difference spacing). M may be any number up to 100 which provides the greatest accuracy. The computation time required is approximately proportioned to M, though the time saved by using less than 100 usually is two small to justify the sacrifice in accuracy. The program automatically computes the difference spacing for the input value of M.

ITMAX   —   This number places a limit on the number of iteration attempts allowed in searching for a solution to the differential equations for any particular value of load. As deformations become increasingly nonlinear, to the point approaching a horizontal tangent of the load-deflection curve, a solution may not exist at a particular load. Under such a condition when ITMAX is exceeded, the load increment is reduced by the program and another solution attemped. A value of 10 for ITMAX is recommended.

ITCYCL   —   This quantity limits the number of times allowed for reduction of the load increment. A value of 5 is recommended for ITCYCL. When ITCYCL is exceeded, the computer run is terminated for that particular problem as the bellows shell is either becoming unstable or the load input is much to large.

KK   —   The quantities to be obtained in the solution of the differential equations are $T(I,1)$ and $T(I,2)$ corresponding to β and ψ respectively in Reference 4A.

When beginning a problem for the first time, the values of $T(I,1)$ and $T(I,2)$ at each point are assumed to be zero for a first guess by KK=1. When a problem is being continued to a higher stress level and a tape has been saved (as described later), the first guess used for $T(I,1)$ and $T(I,2)$ is obtained from the tape by KK=2. In such a case no input is required and should <u>not</u> be used for the geometry since the necessary geometric quantities have been already computed and also appear on the saved tape.

IBND   —   The boundary conditon corresponding to that provided at each end by the attachment to the bellows closures, a value of 1 to 4 is used to provide a condition from fully damped to fully free (see table on the first page of the listing).

KKPRT   —   A print option that allows a print of the final $T(I,J)$ array using KKPRT=1 (used primarily as a diagnostic aid) with KKPRT=0 no array is printed.

KKDEL   —   With a large M, more stress and deflections values are available than usually required to plot distributions across the span. KKDEL provides for saving of computer time by only printing intermediate point stresses while preserving maximum accuracy. KKDEL must be a multiple of M. A value of KKDEL of 4 with M-100 will provide 25 points on a leaf with complete stress and deflection values.

IREG1 and IREG2   –   If stress and deflections on all six leaves is not required, further savings are effected by computing and printing quantities only for the leaves required. The lower limit IREG1 is determined by adding one to:M times the number of the leaf preceding the leaf where stresses are first required. The upper limit IREG2 is determined by adding one to:M times the number of the last leaf of interest. For example, with M=100 if only the central convolution (3rd and 4th leaves) is being studied: IREG1=201 and IREG2=401. To obtain stresses in all six leaves: IREG1=1 and IREG2=601.

LDCASE   –   Three distinct bellows loading conditions may be analyzed by the proper selection of LDCASE. LDCASE 1 represents extension or compression to the limiting stress by either an end force or a pressure differential. LDCASE=3 represents the conditon experienced when a bellows is extended by internal pressure to a given deflection/convolution and is then held at this value by the end of the propellant tank while the pressure continues to rise. LDCASE=2 is the load condition found in a bellow seal device where the bellows is compressed by an end force to a given deflection/convolution and restrained at this value while either internal or external pressure is introduced.

ISTART   –   The end closures may be assumed attached to the end leaves at either the inside diameter (ISTART=1), or at the outside diameter (ISTART=2).

ITAPE – If it is desirable to continue computa-
tions for a particular problem, consider-
able computer time is saved by writing the
last solution array on tape by ITAPE=1;
if a tape is not to be saved by ITAPE=0.

ICASE – When continuing the computations on a
problem using KK=2, the value of ICASE
designates the particular value of
NTRIAL corresponding to the problem as
it was orginally run. This value is to
be found on the print out of the problem
to be continued as case No.

All of the preceding quantities are fixed point inputs.
All remaining quantities are floating point inputs.

RIN – The radius of the inside extremety of the
bellows in inches.

ROUT – The radius of the outside extremety of
the bellows in inches. The effective
span is automatically computed by the
program.

ZRISE – The half pitch of a bellows convolution in
inches.

E – Youngs modulus of the material assumed
for the bellows analysis in psi .

THK – The leaf thickness in inches

PR – Poission's ratio for the bellows material.

RNTM – The allowable computer run time in
minutes. Note: – During program check out
as shown or analyzing a new family of problems
a mimimum time charge value should be used
to avoid excessive cost in the event of
program or geometry errors.

PO   –   The nondimensional initial axial end force related to the end force pounds by:

$$PO = \text{Force in Pounds } \dot{x}\sqrt{12\ (1-PR^2)/2} \ - THK^2$$

Note: PO is in addition to the axial force when a pressure acts on the end closure of the bellows. With LDCASE=3, PO must be 0. A positive PO extends the bellows.

PODEL   –   The nondimensional increment for increasing PO

RHO   –   The initial increment of pressure in psig (positive when the pressure is internal). Note: With LDCASE=2 RHO must be 0.

RHODEL   –   The increment for increasing RHO

SLIM   –   The limiting stress in psi . The program will find the condition of load which causes a maximum stress equal to SLIM within a given error ERRS.

ERRF and ERRG   –   Nondimensional error controls for the differential equation solution. A value of 0.001 for each will produce sufficient accuracy. The influence of ERRF and ERRG is best observed by using several values and observing the differences in stress and computation time.

RESMAX   –   A nondimensional overflow guard. A value of 10^6 is recommended.

FAC   –   A reduction factor to be applied to PODEL or RHODEL when searching for a solution. (See discussion for ITCYCL). A value of 0.5 is recommended.

FACIN   —   When the value of PODEL or RHODEL is so
small that less than 3 iterations are
required for solution at each load,
PODEL or RHODEL is increased by the factor
FACIN to reach SLIM in less computation
time.

WBL   —   The weld bead cross section dimension in
the plane normal to the bellows centerline
in inches

WBW   —   The weld bead cross section dimension
parallel to the bellows centerline in
inches.

WTOTMX   —   The limiting deflection/convolution in
inches of the middle convolution LDCASE=
2 or 3 (positive for LDCASE=3, negative
for LDCASE=2).

ERRS   —   Allowable error between maximum computed
stress and SLIM. Input as the square of
the actual error desired. For example,
if the stresses and deflection are
desired corresponding to a condition of
load producing a maximum bellows stress
equal to SLIM within 100 psi, use 10000.
for ERRS. This quantity is always positive.

DFERR   —   The allowable error between the actual
deflection/convolution and WTOTMX in
LDCASE=2 or 3. Input as the square of
the actual error limit desired in inches.
For example, if the deflection/convolution
in LDCASE 3 is desired held at WTOTMX
within 0.001 inches, use 0.000001. This
quantity always positive.

POICON   —   In LDCASE=2 or 3 conditions the end
reaction force to hold WTOTMX within
DFERR is found by the program through
application of POICON. This quantity
is corrected and updated to account for
nonlinearities of spring rate or a slightly
incorrect input value of POICON. The
reasonably close estimate required for

this input quantity may be obtained as
follows:

From separate computer runs with LDCASE=1
for PO and RHO loadings, find the values
of PO and RHO which produce the same
deflection in the middle convolution. Then

$$POICON = PO \cdot E \cdot THK^2 / RHO \cdot RIN^2 \cdot \sqrt{12(1-PR^2)}$$

The remaining input required is concerned with the geometric description of both the even and odd numbered leaf contours. The geometric quantities required by the main computer program are provided by a subroutine GEOM. A subroutine GEOM Fortran II listing is provided which is applicable to a great number of leaf contours made up of sections of circular arcs and straight lines.

Since an infinite variety of leaf contours are possible which cannot be handled by the subroutine given here, the analyst may need to write additional subroutines. This task is relatively simple when the nature of the required geometric information is understood.

All geometric information supplied to the main program by the subroutine must be in nondimensional form. All quantities measured in inches are nondimensionalized by dividing by RIN. The nondimensionalization may be done by the subroutine. The subroutine then divides the developed length of each leaf into M equal spaces. The resulting spacings are designated by H1 and H2 for the odd and even numbered leaves respectively. At each of the equally spaced points on all six leaf mid surfaces, the subroutine computes the coordinates $R(I)$ and $Z(I)$. $R(I)$ is the radial location and $Z(I)$ is the distance parallel to the bellows axial centerline from a convenient reference plane such as the end bellows closure point. The subroutine must also supply at each point the first and second derivatures of R and Z with respect to ξ , which is the coordinate along the leaf midsurface. The first and second derivatives of R and Z are called $RP(I)$, $RPP(I)$, $ZP(I)$, and $ZPP(I)$ respectively corresponding to r_0', r_0'', Z_0', Z_0'' in Reference 4A. One other set of derivatives is required by the main program because of the discontinuities that exist at the five points where neighboring leaves are joined. The special derivatives are required for the juncture point on the second of the two adjoining leaves. Thus at the joint between the first and second leaves the subroutine must determine RP21, RPP21, ZP21 and ZPP21 which are the first and second derivatives with respect to ξ , of R and Z respectively, on leaf number 2 at the juncture of leaves 2 and 1. Similarly the remaining four groups of special derivatives called RP32, RPP32, ZPP32, RP43, RPP43, ZP43, ZPP43, --- ZPP65 are computed.

The geometric input quantites for the subroutine GEOM
provided here are shown in Figure 5.0-1. All radii and flat
section lengths inputs are in inches and all angles inputs
are in radians. The subroutine listing given contains
several subroutines that are selected by the input quantities
ZR and GC. If all six leaves have the same developed length,
ZR=zero. If the odd numbered leaves have different developed
length, than the even number leaves, ZR=1.0. When a straight leaf
shape is desired, GC=1.0 and all Figure 5.0-1 dimensions
are zero. When GC=2.0, the appropriate quantities from
Figure 5.0-1 are used with ZR always equal to 1.0. If
GC=2 and all leaves are the same, this fact will be reflected
by the Figure 5.0-1 input values. GC=3.0 used with ZR=0.0
computes the special cases of one, two or three arc shapes
where the mulitple arc shapes have equal radii. The input
quantities RX and RY, required only for this special case
are defined in Figure 5.0-2. Note that only the angle THA1
is required for this special case. Quantities RX and RY
as well as quantities from Figure 5.0-1 which are not
required for a particular problem are zero inputs. Thus any
portion of the general shape of Figure 5.0-1 may be deleted
and the subroutine will automatically join the desired sec-
tions together without discontinuity.

Various output results may be printed, depending on the
problem and the choice of input loading. If the input load
is too large, the solution will not converge as detected
by the RESMAX input. When this condition arises, the print
out will be "(RESF + RESG) exceeds RESMAX." When ITCYCL
is exceeded (as discussed in the input explainations), the
print out will be "ITCNT has exceeded ITCYCL." Under certain
conditions the computer run may be terminated by excessive
computation time. This condition is identified by comparing
the printed "Run Time" value with the RNTM input. With
successful convergence in the alloted RNTM, the print out
will contain the following quantities at each point, selected
for print by KKDEL:

The first page prints some of the pertinent input for
identification. In addition to repeating inputs "CONV
VOLUME" is printed. This is the volume of material in one
convolution. The "DEVELOPED LENGTH" is in inches. "PTOT"
is the total end force in pounds applied by PO and/or the
pressure, RHO, acting on the area of the bellows end closure.
"NCNT" is the number if iterations required for the solution
at the value of PO or RHO printed. "ITCNT" is the accumu-

number of times that the load has been reduced in reaching
the solution as it is printed.

"R" and "Z" are the coordinates in inches provided by the
subroutine GEOM.

"SLONGM" and "SLATM" are radial and circumferential membrane
stresses, respectively, in psi positive in tension.
"SLONGB" and "SLATB" are radial in circumferential bending
stresses, respectively, in psi positive when there is tension
on the inside bellows surface.

"SSHEAR" is the transverse shear stress (psi) positive when
the shear acts so as to rotate on element of the shell
counterclockwise. "DEFLAX" and "DEFLRD" are the axial and
radial components of displacement (inches) positive in the
positive directions of the coordinates R and Z.

"DELS" is the change in the straight line distance between
neighboring KKDEL points, (inches) e.g. the second value
printed, with KKDEL=5, is the change in distance due to dis-
placement between point one and point six.

"SLTWM" and "SLTWB" are the circumferential membrane and
bending stresses, respectivley, in the weld bead.

Four fluid volumes/convolution - (inches^3) are printed; two
in the orginal underformed position and two in the deformed
position. The "VOLUME BETWEEN LEAVES" is the volume in
the middle convolution between RIN and ROUT. The "VOLUME/
CONVOLUTION" is the total volume of the middle convolution
from the bellows centerline to ROUT.

"SMAX" is the maximum combined bending and membrane stress
in the bellows within the regions IREG1 and IREG2. The
maximum stress may be located between points printed by
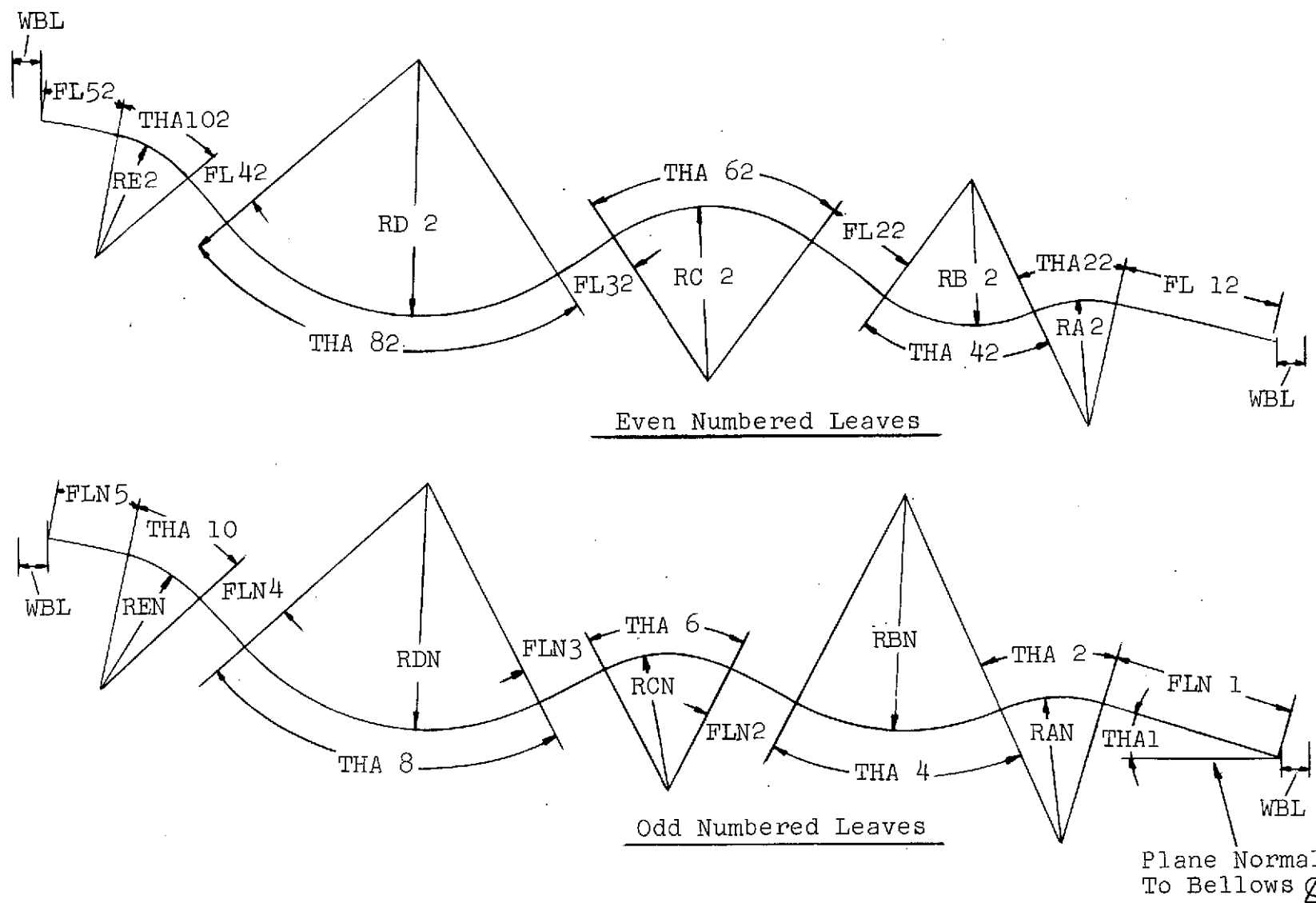KKDEL so that the location is shown by "RDIMX" and "ZDIMX".

FIGURE 5.0-1   SUBROUTINE GEOM INPUT PARAMETERS FOR LEAF MIDSURFACE CONTOUR
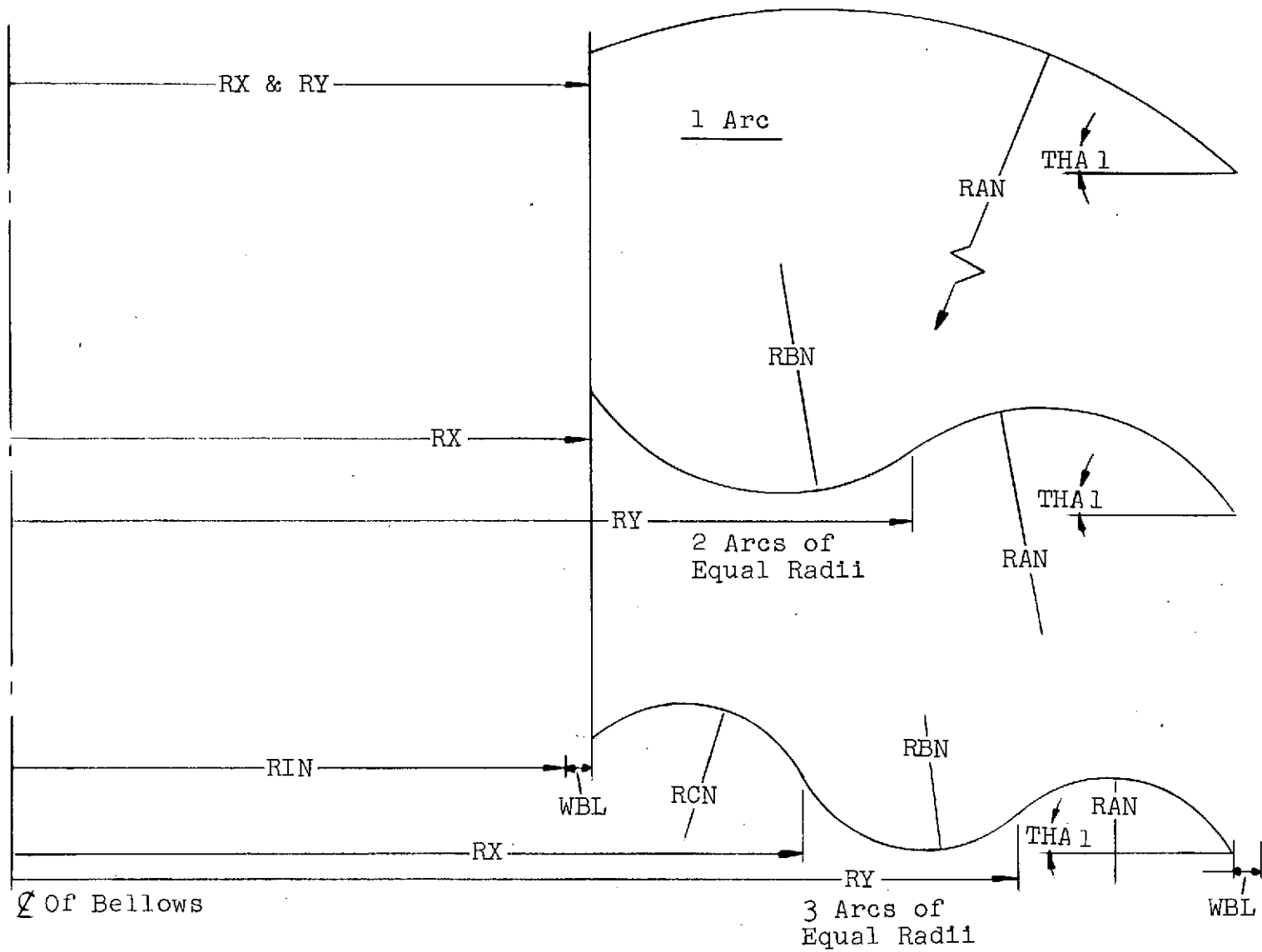
FIGURE 5.0-2   SPECIAL SUBROUTINE GEOM INPUT PARAMETER GC = 3.0
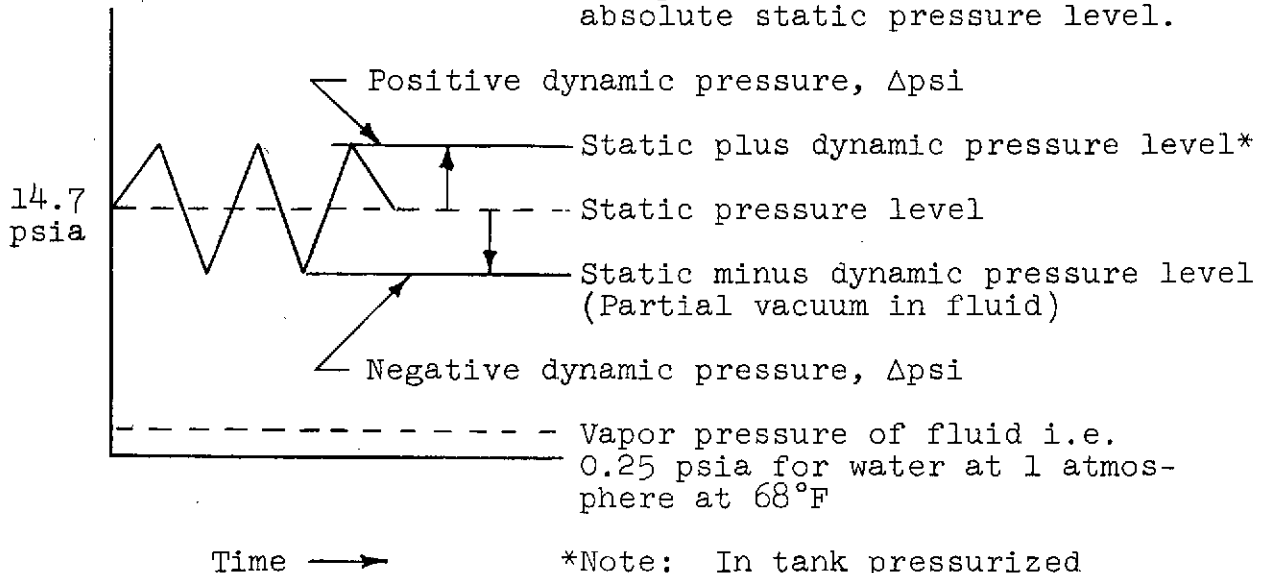
6.0   REFERENCES

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APPENDIX III

DEFINITIONS

ACCELERATION: A vector quantity that specifies the time rate of change of velocity.

ACCORDION, MODE: A longitudinal vibration mode characterized by convolution motion parallel to the longitudinal axis of the bellows with little or no bellows head motion.

AMPLITUDE: The maximum value of sinusoidal

ANTIMODE: Point having maximum motion.

AREA, EFFECTIVE: That surface on which pressure acts to produce motion of the bellows

$$\approx \frac{(OD + ID)^2}{4}$$

BAFFLE: A third leaf welded in at the outside diameter and protruding into the liquid column.

BUCKLING, ASSYMMETRIC, NON SYMMETRIC OR UNSYMMETRIC :   A buckling mode where changing leaf contour departs from a surface of revolution.

BUCKLING, AXISYMMETRIC OR UNSYMMETRIC: A buckling mode where the changing leaf contour remains a surface of revolution.

BUCKLING, GENERAL: Change of leaf contour without any increase in applied load or pressure.

CONTOUR, BASIC: Shape of bellows leaf on a radial section.

CONVOLUTION: Two leaves weled together at the I.D.

CORRUGATION: (See Ripple)

COULOMB, DAMPING:
(dry friction damping)   Dissipation of energy by a force whose magnitude is a constant independent or displacement and velocity.

DAMPING:	Dissipation of energy with time or distance.
DEFLECTION:	Motion at any pint in the bellows due to load relative to its original no load position. It is increment of travel.
DIAMETER, INSIDE:	(I.D.): Inside diameter of bellows assembly.
DIAMETER, MEAN:	The diameter measured at the midpoint on the span.

$$\frac{O.D. + I.D.}{2}$$

DIAMETER, OUTSIDE:	(O.D.): Outside diameter of bellows assembly.
DISPLACEMENT:	A vector quantity that specifies the change of position of a body or particle and is usually measured from the mean position of rest.
DISTORTION:	An undesired change in wave form.
DYNAMIC PRESSURE:	The pressure variation about the absolute static pressure level.

Positive dynamic pressure, Δpsi

Static plus dynamic pressure level*

14.7 psia — Static pressure level

Static minus dynamic pressure level (Partial vacuum in fluid)

Negative dynamic pressure, Δpsi

Vapor pressure of fluid i.e. 0.25 psia for water at 1 atmosphere at 68°F

Time ⟶

*Note: In tank pressurized application this becomes maximum expected operating pressure.

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EFFICIENCY, EXPULSION: Ratio of loadable volume of propellant to usable volume.

EFFICIENCY, VOLUMETRIC: Ratio of usable volume to total enevelope volume.

ELASTIC STRAIN REGION: The region over which the bellows can be extended without sustaining a permanent deformation in the convolutions, i.e., region were stress is proportional to strain.

ENVIRONMENT: See natural environments and induced environments.

EXCITATION (stimulus): An external force (or other input) applied to a system that causes the system to respond in some way.

EXPULSION CYCLE: Cycle of bellows operation from stacked height to extended length (bellow filled with propellant) and back to stacked height (propellant completely expelled).

FLEXIBILITY: Deflection per unit of applied load or pressure.

FLIP: Abrupt or unstable opening or closing of a convolution during expulsion cycle.

FREE LENGTH: Length of bellows with zero psi pressure difference across the bellows, equilibrium point of bellows.

FREQUENCY: Reciprocal of period. The unit is the cycle per unit time and must be specified.

FUNDAMENTAL FREQUENCY: Lowest natural frequency.

g Applied test level acceleration divided by earth's gravitational acceleration.

GEOMETRIC NONLINEARITY:

The condition in which bellows leaves are in the elastic strain region during loading and unloading, with the load-deflection relationship following a curved rather than a straight-line path. The geometric non-linearity region is characterized on the hysteresis loop as being a curved, reversible path.

HARMONIC:

Sinusoidal quantity having a frequency that is an integral multiple of the frequency of a periodic quantity to which it is related.

HEIGHT, STACKED:

Distance from the center of the weld bead on the first convolution (or attachment point) to the center of the weld bead on the last convolution when bellows assembly is nested.

HYSTERESIS:

Area between extension and compression curves of spring rate.

INPUT:

Any applied test level.

LATERAL MODE:

A vibration mode characterized by a sideward or lateral motion of bellows. At fundamental or lowest lateral mode the center convolution moves in a direction which is at all times perpendicular to the longitudinal axis of the bellows and the other convolutions are rocking about the longitudinal axis.

LEAF:

Individual bellows shell element.

LENGTH, EXTENDED:

Length of bellows measured from center of attachment weld to center of the weld bead on last convolution at full extension.

LENGTH, FREE:

The equilibrium point of the bellows assembly. The length the bellows assumes when not acted upon by an external force.

LENGTH, NESTED:

(See Height, Stacked)

LIFE, CYCLE:

The number of complete expulsion cycles before failure.

LINEAR ELASTIC:

The condition characterized by very small leaf deflection where the stresses are very small and caused largely by bending action. The diaphragms are obviously in the elastic strain region with the load-deflection relationship following a straight-line path during loading and unloading. The linear elastic region is characterized on the hysteresis loop as being a straight, reversible path.

LINEARITY:

Constant rate of stroke with pressure.

LINEAR SYSTEM:

A system is linear if for every element in the system the response if proportional to the excitation.

LIQUID MODE:

A longitudinal vibration mode characterized by longitudinal convolution tip motion, bellows head motion, and internal pressure oscillations.

LOAD, ACISYMMETRIC:

A load which has no variation along a circumferential path of constant radius.

MODE OF VIBRATION:

Characteristic pattern of convolution displacement during vibration.

NATURAL FREQUENCY:

The frequency of free vibration of a bellows, also the frequencies of the normal modes of vibration.

NODE:

Point having zero motion relative to earth, or on a bellows where minimum convolution motion occurs during vibration.

NONLINEAR DAMPING:

Where the damping force is not proportional to velocity.

NORMAL MODE OF VIBRATION:

Where vibration occurs uncoupled from (i.e. can·exist independent of) other modes of vibration of a bellows.

OIL CAN:

See "Buckling, Assymmetric"

PERIOD:

Smallest interval of time for which the displacement repeats itself.

PHYSICAL NONLINEARITY:

The condition resulting when the bellows material is stressed beyond its elastic limit, i.e. into the inelastic or plastic strain regions. The leaves are no longer in the elastic strain region and the load-deflection relationships, although following a curved path on the hysteresis loop, differe during loading and unloading. The more the loading is increased beyond the elastic limit the greater the area of the hysteresis loop. The region is characterized on the hysteresis loop as being a curved, irreversible path.

PITCH:

Axial distance from the center of the weld bead on one convolution to the ceter of the weld bead on adjacent convolution.

PITCH, DESIGN:

The maximum pitch at which the bellows assembly will operate reliably for the design cycle life.

PITCH, NESTED:

Distance between the centers of adjacent weld beads in nested (stacked) position.

PLASTIC STRAIN REGION: The region beyond the elastic strain region in which the bellows sustains appreciable permanent deformation without rupture, i.e. region beyond the yield point region of physical nonlinearity.

PLY: Number of leaf thicknesses.

POINT, PIVOT: (See Free Length)

POWER SPECTRAL DENSITY: The limiting mean - square value (e.g. of acceleration or other random variable) per unit band width.

PRESSURE, DIFFERENTIAL (P):   Pressure differential across bellows.

RANDOM VIBRATION: Where the instantaneous amplitude cannot be specified for any instant of time. Bellows amplitudes and number of peaks can be established using statical means for practicle cases.

RESONANCE: Where any change, however small, in the frequency of excitation causes a decrease in the response of a bellows.

RESPONSE: Motion or pressure resulting from an excitation (input).

RIPPLE: A contour of leaf (corrugation). (See Contours, Basic)

RIPPLE, MIRROR IMAGE: Leaves are fabricated from mating dies with preset free length.

RIPPLE, NEUTER: Leaves are fabricated using the same die for better nesting characteristics. This requires that free length be set after assembly, normally at one-half of design pitch.

SCAN: | A low level sine vibration transverse over a given frequency range to obtain response data.

SINUSOIDAL MOTION (Simple Harmonic Motion) | Where the displacement is a sinusoidal function of time.

SPAN: | Width of convolution measured from O.D. to I.D.

$$\frac{O.D. - I.D.}{2}$$

SPAN, EFFECTIVE: | Span measured between welds where the leaf has constant thickness.

SPRING RATE: | The ratio of change of force to change of deflection expressed in lb per inch.

STROKE: | (See Travel).

TRANSMISSIBILITY: | Nondimensional ratio of the response amplitude to the excitation amplitude e.g. output acceleration divided by input acceleration.

TRAVEL: | Length of bellows at extension measured from the center of weld bead of end convolution at stacked height to the center of the same weld bead when fully extended to design pitch.

$$(P_d - P_s). \ Nc$$

VIBRATION: | An oscillation or variation with time of a quantity with respect to a specified reference.

VISCOUS DAMPING: | Dissipation of energy by a force proportional to velocity.

VOLUME LOADABLE: | The volume contained withing the bellows assembly at design pitch.

$$Vol \approx \frac{\pi}{4} . \ D_m^2 \ (P_s - P_d). \ Nc$$

D_m = Mean diameter

P_s = Pitch at stacked height

P_d = Design pitch

Nc = Number of convolutions

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